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ORIGINAL ARTICLES.

The Geology of the Lower Shire–Zambezi Area.[1]

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(PLATE IV.)

THE area lying between the Lower Zambezi and its northern tributary the Lower Shire forms a relatively small salient between the better-known parts of Portuguese East Africa [2] lying to the north and to the south, and a study of its geology in relation to that of the larger territory has yielded interesting results. The area described includes the southern end of the Nyasaland Protectorate and that part of Portuguese East Africa lying between it and the Zambezi.

The Crystalline Series.—The Port Herald Hills and the country lying between them and the Zambezi consist mainly of ancient sediments that show widely varying degrees of metamorphism (III (9)) [3]; these sediments have been invaded and in many cases extensively altered by various intrusives. Apart from the pebbles included within the Nachipere conglomerates, which consist of felspathic, micaceous, and hornblendic gneisses apparently of igneous origin, no trace of rocks older than the sediments has been recognized, and in this and other respects the general results resemble those yielded by the Mafingi sediments that make up a large part of northern Nyasaland. The later fieldwork on the pre-Karroo of the present area, as well as part of that on the Karroo rocks themselves, has been carried out jointly by my colleague, Mr. C. B. Bisset, M.A., B.Sc., D.I.C., and myself during the field-seasons of 1928 and 1929.

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[1] Paper read before Section C (Geology) of the Brit. Assoc. Adv. Sci., S. African meeting, 1929.

[2] A. A. Freire d'Andrade, *Esboço Geológico da Provincia de Moçambique,* 1928.

[3] The numbers in parentheses refer to the Bibliography on p. 60.

The sediments are exposed in their least altered form in the valley of the upper Nachipere and in the hilly country lying between the Port Herald Hills and the Zambezi. Apart from the upper Nachipere and several similar but smaller areas, the Port Herald Hills consist very largely of banded hornblendic, micaceous, and quartz-bearing felspathic gneisses, often garnetiferous, interbanded with quartzites, magnetite-quartzites, graphitic schists, and white crystalline dolomitic limestones, and the evidence from a number of localities is clear that these gneisses and schists have been derived from the metamorphism of the Nachipere sediments. This metamorphism is in part of regional character, since it is present throughout the whole of the area described, but in the Port Herald Hills it is in general intensified by the effect of numerous intrusions of varying size and composition; the Port Herald Hills in part owe their greater altitude, as compared with the remainder of the outcrop of the sediments, to this additional metamorphism and to the presence of the associated intrusives.

A few miles north of the Nachipere a series of magnetite- and ilmenite-bearing quartzites occurs around the head of Naminjale Stream and along Nankande Stream; the relation of these beds to the Nachipere sediments and the gneisses of the Port Herald Hills was at first doubtful, but additional more detailed observations both in the hills themselves and in the country to the west have demonstrated that these rocks all belong to one large group, for which the name Nachipere Series is proposed. Furthermore, the pre-Karroo rocks of a large part of southern Nyasaland are not distinguishable from those of the Port Herald Hills.

The sediments of the upper Nachipere comprise a group of coarse conglomerates, arkoses, and quartzites, together with argillaceous, calcareous, and carbonaceous beds. These rocks have undergone varying degrees of metamorphism and deformation, so that they can be observed locally to pass over into partly or wholly re-crystalized gneisses, felspathic quartzites, and micaceous and graphitic schists. In the Nachirenda valley north of Lulwe Hill the common white crystalline limestone of the Port Herald Hills is interbanded with altered pebbly grits and arkoses. On the Chididi-Tangasi track several miles from Guta village, pebbly grits and de-silicified sandstones form bands or lenticles within the sedimentary gneisses; they are interbanded also with black platy hornblendite that appears to represent an altered igneous rock.

The deeply-dissected country lying between the southern part of the Port Herald Hills and the strip of Karroo basalt running east of the Zambezi is made up of hard quartzitic grits, interbedded with crystalline limestones and graphitic schists, gneisses, and quartzites, with a subordinate development of micaceous and hornblendic schists. The beds are vertical or steeply inclined, the dip being generally towards the north-north-west; the strike is mainly E.N.E.–W.S.W., but may vary within 20° of this direction.

The quartzites are of medium grain, occasionally pebbly, and variably felspathic; they are sometimes slightly calcareous, with the result that a white calcareous skin appears on weathering. They weather to a white or light greyish colour, and they are frequently spotted with small red garnets. The limestones are usually white, of medium texture, and variably intermixed with mineral impurities, including biotite, pyroxenes, and graphite. The graphitic rocks range from graphitic quartzites to graphite-schists, and clearly represent altered carbonaceous sediments. The outstanding peaks and ridges of the area, such as Domwe and Nyapanda (Figs. 1 and 2, Pl. IV), consist essentially of steeply-inclined quartzitic grits, with subordinate quartzites, that locally show a faint parallel structure or pass into quartzitic schist. On the crest of Nyapanda is a thin band of a dense, dark garnetiferous rock, and on the southern slope the following rocks appear in descending order; banded quartzitic gneiss, with pegmatite and granitic veins; white crystalline limestone; dark, hornblende-schist; and white quartzites, containing large blocks of iron ore; soft white micaceous schist; quartzitic garnet-mica-gneiss with granitic veins. For several miles north-east and south-west of Nyapanda a group of rocks consisting largely of crystalline limestone with soft white quartzites dips steadily beneath the magnetite-quartzites and the grits. As Chivumbvu Stream is approached about 3 miles north-east of the hill the sediments gradually loose their regular dip and become more and more contorted and metamorphosed; in the bed of the stream the rocks comprise intensely foliated greyish garnetiferous quartzites, biotite-quartzites, and quartzite schists; these rocks show veins and *lit-par-lit* injection of granite, intersected by biotite-pegmatite.

The Nyapanda rocks continue westward until they pass beneath the Lupata Sandstones; near the unconformity good sections in the Ngoma River expose hard white flaggy quartzites that often carry biotite and garnets, and are locally rich in streaks and lenticles of iron ore, so that they closely resemble the Naminjale beds.

Lulwe peak and the high ridge running to the north consist of members of the grit series altered to biotitic, hornblendic, and graphitic gneisses by intrusions of hornblende-syenite and nepheline-syenite. The country to the west as far as Domwe, and southwards into Portuguese territory, consists almost wholly of pale garnetiferous grits and quartzites interbedded with graphitic rocks and lenticles of white crystalline limestone.

Intrusives into the Nachipere Series.—The intrusives include principally in order of injection, syenite, hornblende-syenite, and biotite-syenite, all showing granitic variations and possessing a wide range of gneissose structures; syenite-pegmatite; nepheline-syenite and nepheline-pegmatite; quartz veins; dolerite of Karroo age as dykes and other intrusions; rhyolitic and other highly-siliceous rocks intruded into faults of early post-Karroo age; and an ultrabasic intrusion, probably of late Tertiary age, is represented by pebbles in the bed of the Nachirenda.

The earliest intrusions were accompanied by powerful stresses that caused intense folding and contortion in the sediments; for these rocks are intricately veined and often impregnated by the magma, which has itself clearly been involved in the same movements that affected the sediments. The later syenitic intrusions were injected under less disturbed conditions, but they show great variations in the degree of foliation, even within the one mass; they were followed by numerous pegmatites that are for the most part unfoliated.

The later syenites pass locally into nepheline-syenites that are generally rich in biotite and strongly foliated; they are followed by nepheline-felspar-pegmatites that are sometimes rich in magnetite. These nepheline-syenites (Fig. 3, Pl. IV) are usually associated with small deposits of corundum. Numerous small independent intrusions of nepheline-syenite are known within the Port Herald Hills and the country to the west; they show great variation in the proportions of nepheline, felspar, and biotite. These alkaline intrusives are similar to those near Liwonde (III (9)) and farther north, but differ from those occurring around the southern end of Lake Chilwa (see below, p. 56). Chuara Hill, lying 22 miles north of the upper end of Lupata Gorge, is an alkaline intrusive of different character from those of the Port Herald Hills, and Mr. Campbell Smith has compared it with certain Abyssinian rocks described by G. T. Prior as quartz-lindöite. Representatives of the earliest Lupata volcanic rocks rest upon the flanks of the hill. Several miles east-north-east of Chuara is a large area of dark gneissose olivine-norite that is probably of pre-Karroo age; it forms at least part of Nkunga Hill and the surrounding country.

The occurrence of numerous alkaline intrusions in Nyasaland is of interest in view of the absence of records of such rocks in adjacent countries. It may be anticipated that more detailed examination of these territories will reveal many additional outcrops, for during recent reconnaissances in North Eastern Rhodesia and Portuguese East Africa the writer has found that these intrusives are present amongst the ancient sediments there much as they are in Nyasaland.

In general, the intrusives have intensified the metamorphism of the sediments, and have often impressed upon them, as a result of intimate injection, the character of composite gneisses. Accordingly, in the Port Herald Hills, where a succession of granitic and syenitic magmas appeared, the metamorphism is of a much higher order than in the country between the hills and the Zambezi, where intrusive action has been relatively very slight. Similarly in the Shire Highlands, where there are numerous intrusions, including the relatively large masses of Mlanje, Zomba, and Chiradzulu, the degree of metamorphism resembles that of the Port Herald Hills.

Comparison with other Areas.—In Portuguese East Africa south of the Zambezi E. O. Teale (VIII (2)) has described widespread fragments of an ancient sedimentary system that exhibit various stages of metamorphism. The rocks include a great development of quartzites and quartz-schist, such as those of Shimanimani and Statonga, as well as felspathic, micaceous, graphitic, and quartz-magnetite-schists. In the Manica area the rocks consist of a varied succession of altered sediments, including conglomerates, quartzite, quartz-schist, " banded ironstone ", argillaceous schists and phyllites. Calcareous rocks appear to be rare. The sediments have been intensely folded and invaded by granite and by biotite- and hornblende-granite-gneiss, as well as by basic rocks. Various banded and composite gneisses, in part at least of sedimentary origin, have also been invaded by these magmas. While admitting that the relationships of the different groups are obscure, Teale puts forward a provisional succession in which the composite gneisses and crystalline schists in part, regarded as the oldest rocks, are followed by the Shimanimani and Statonga quartz-schists, and these by the Manica schists.

There can be but little doubt that the ancient sediments north of the Zambezi now described are in general equivalent to those observed by Teale from south of the Zambezi. But observations in the Port Herald Hills and adjacent country lead to the conclusion that all the ancient sediments there exposed form parts of one great sedimentary system that has been intensely folded and subject to varying degrees of metamorphism ; locally the sediments have been intimately injected by acid and intermediate magmas that have effected yet further alteration, with the result that every gradation can be observed between slightly altered sediments and thoroughly recrystallized gneisses. All these rocks, which constitute the oldest formation yet recognized in the area, have been invaded by biotitic and hornblendic, often gneissose, syenites passing to granite, by biotite-syenite passing to nepheline-syenite, and by various pegmatites.

Quartz-schists, quartz-felspar-schist, and quartz-magnetite-granulite showing varying degrees of metamorphism, together with crystalline limestones, are recorded also from amongst the oldest known rocks of Northern Mozambique, where the succession as described by Holmes (IV) is essentially similar to that now outlined for the Lower Shire-Zambezi area. Furthermore, in the association of thick beds of white crystalline limestone with a wide range of metamorphosed sediments the Nachipere Series resembles the Turoka Series and related rocks described by Parkinson (VI) from Tanganyika and Kenya, and in this connection it should be mentioned that several years ago Parkinson expressed the opinion (VI (2), p. 608), that the Turoka Series would be found to extend at least as far south as Nyasaland.

It is probable that the Nachipere Series will prove to be extensively developed in the southern and central parts of

Nyasaland; for not only do the schists of the Shire Highlands bear a general resemblance to the more highly metamorphosed sediments of the Port Herald Hills, but also crystalline limestones, graphitic schists, and quartzitic schists have been recognized in many localities. Moreover, crystalline limestones, and graphite-, felspar-, quartz-, and mica-schists are well represented amongst the crystalline rocks of Angoniland (I). Finally, the intrusive history of these different areas closely resembles that of the Port Herald Hills, except that in the Ncheu area, where older rocks may be represented, there occur also numerous basic and ultrabasic masses in which the asbestos deposits are situated (III (9)).

A close comparison can be drawn between the Nachipere Series and the Mafingi Series of northern Nyasaland (III (9)), not only in the lithological character of the sediments but also in the variable metamorphism and the intense compressive stresses to which they have been subjected, and in the nature of the rocks by which they have been invaded.

An attempt to correlate the Nachipere Series and the Mafingi Series with the older formations of Southern Rhodesia still presents considerable difficulties. But it may be mentioned that in many respects the Mafingi Series is closely comparable with the Lomagundi System, which is probably of Transvaal age, and that the Nachipere Series has more in common with this system than with the Basement Schists of that country. Moreover, the Shimanimani Quartzites of the Frontier System, which is separated by faults from neighbouring formations, so closely resemble the thicker quartzites of both the Mafingi and the Nachipere Series that it would appear possible that they also belong to the Lomagundi System.

Pre-Karroo Sediments.—On the frontier of Portuguese East Africa and Southern Rhodesia there occurs a system of sediments called the Sabi Series by Mennell (V (i)) and the Spungabera Series by Teale (VIII (2)); it is known in Southern Rhodesia as the Umkondo System, which is regarded as possibly representing the Waterberg. The beds lie at gentle angles and rest unconformably upon the granite-schist complex. The basal beds in the Sabi Valley consist of bluish-grey limestone, several hundred feet in thickness, followed by purplish shales, sandstones and quartzites associated with andesitic amygdaloid; above these lower beds come hard grey sandstones to a thickness of several thousands of feet.

In the present area Muambe Hill, north of the upper end of the Lupata Gorge, consists of gneisses overlain by about 200 feet of almost horizontal grey limestone followed by fully 1,000 feet of hard grey quartzitic grit; the junction between the grit and the limestone is obscured by fallen blocks. The grits make up the greater part of Muambe, and they give rise to several parallel ridges that rise abruptly to a height of 1,300 feet above the adjacent Karroo lowlands, against which they are faulted for at least part of their length. The upper part of Chilwa Island in southern

Nyasaland, as well as Tundulu Hill at the southern end of the lake, consist of limestone of similar character ; here, as also at Muambe, the limestone is locally impregnated with manganiferous iron ores. Both on the island and on the mainland the limestone exceeds 700 feet in thickness and is practically horizontal ; on the island it rests upon various gneisses.

The lithological and structural characters of these sediments strongly suggest that they are to be referred to the Umkondo System, and this view is supported by their relations to the crystalline series and to the Karroo. If these considerations prove correct the beds constitute the first representatives of the Umkondo System to be recognized in Nyasaland.

It is of additional interest that the Chilwa limestone has been invaded successively by syenite, nepheline-syenite, and nepheline-bearing dykes (see below, p. 56).

Karroo.—The Karroo of the Lower Shire-Zambezi area (III (8)) has yielded results of especial interest. On stratigraphical grounds, and by means of various fossils including reptiles, lamellibranchs, ostracods, fish-scales, wood and plants, determined by Dr. S. H. Haughton and Mr. John Walton, it has been possible to recognize the Ecca, Lower Beaufort, and Stormberg stages. Beds containing *Rhexoxylon africanum* rest directly upon beds assigned to the Lower Beaufort, and accordingly the upper divisions of the Beaufort appear to be absent. The uppermost Stormberg strata include desert sandstones comparable with the Forest sandstone. The *Rhexoxylon* beds are considered to represent in part the Somabula beds of Southern Rhodesia, but the concentrates from the Lower Shire sediments are of different character and have not as yet been found to yield any gemstones. The volcanic rocks succeed the desert beds and comprise a great thickness of basalts with interbedded rhyolitic lavas and tuffs comparable with those of the Lebombo Mountains ; moreover, the main boundary faults have been injected by later rhyolitic rocks, carrying small quantities of gold, as well as by siliceous and calcareous rocks indicative of hydrothermal or solfataric action.

The Karroo of this area shows interesting relations to that of Cape Province, Rhodesia, and Tanga (III (8)).

Cretaceous.—The Lupata sedimentary and volcanic rocks (V, IX, III (7)), rest upon a deeply-eroded surface of the Karroo and the pre-Karroo. The volcanic rocks include an earlier rhyolitic series and an unconformable alkaline series ; outcropping in their midst, and of later age, are intrusions of nepheline-syenite, microfoyaite, and tinguaite.

The rhyolitic series has been recognized only in the country around the head of Lupata Gorge and in the hills north of Mutarara, and although the sub-divisions of the series in these two areas do not appear to correspond, yet there can be no doubt as to the general equivalence of the two groups ; for in the Lupata area the rhyolites are overstepped by the upper Lupata Sandstones and the succeeding alkaline lavas, and in the Mutarara area the rhyolites are overstepped by sandstones that can be followed along the north bank of the Zambezi until they join the Upper Sandstones of Lupata Gorge. Moreover, along the foot of the hills above Old Mutarara unconsolidated gravels of Recent age contain small alkaline pebbles, but such pebbles have not been observed by the writer in the sandstones overlying the rhyolites.

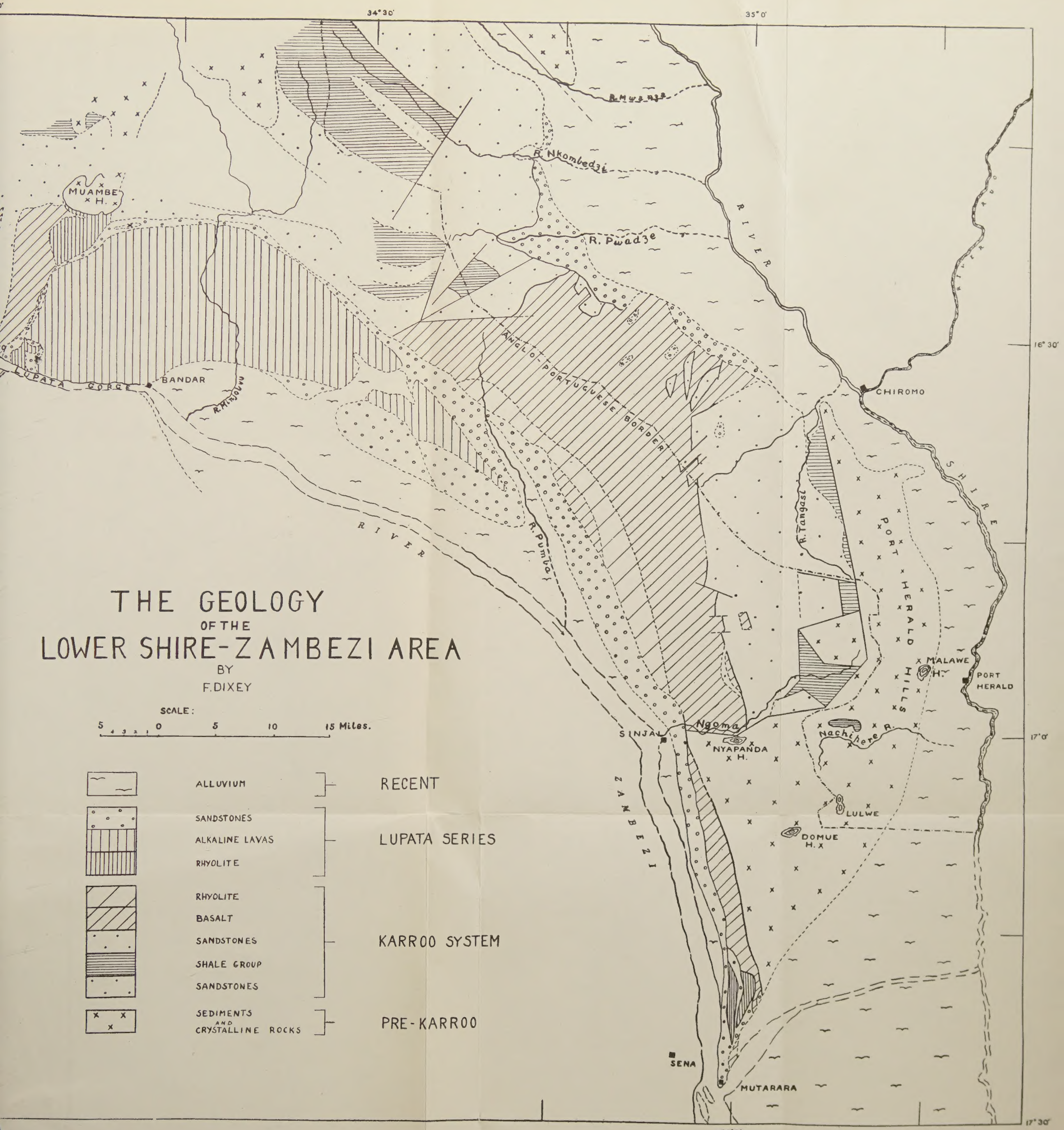
The Mutarara rhyolitic rocks form two groups that alternate with pebbly sandstones, but it is of interest that rhyolite pebbles occur also within the sandstones underlying the earlier group. When followed northwards the rhyolites begin to thin out before they are overstepped, but the sandstones separating them increase in thickness; about 10 miles above Mutarara these sandstones step across the lower rhyolites on to the Karroo basalts, but the upper rhyolites thin out almost completely on to the sandstones before they are cut out by a younger group representing the Upper Lupata Sandstones.

The Lupata Sandstones, recognized also in the Lower Shire Valley, closely resemble the Dinosaur Beds of North Nyasa (III (4)), and in this and other respects recent work tends to confirm Mennell's view (V (2)) that the Lupata Series dates back to the beginning of the Cretaceous.

To the south of Lake Chilwa in the southern part of Nyasaland, in an area lying 125 miles east-north-east of Lupata, the writer has recently observed evidences of an intrusive and volcanic episode that has several features in common with that of the Lupata area. This episode has not hitherto been recognised in Nyasaland, and its position in one of the branches of the Rift Valley raises points of especial interest. The order of events in the area was essentially as follows:—Syenitic intrusions of variable character were perforated by large volcanic vents from which rhyolitic lavas and ashes were discharged; nepheline-syenite was then intruded at many points, and was followed by numerous related minor intrusions; the youngest rocks include ultrabasic dykes comparable with those intersecting the late Tertiary sediments of Sheringoma plateau, as was first brought to my notice by Mr. Mennell, as well as necks and dykes of dark nepheline-bearing rocks.

Apart from minor fissures, which have been recognised from several points in southern Nyasaland, two well-defined vents are known near the southern end of Lake Chilwa; the larger of these is well preserved and is fully half a mile in diameter. But denudation has been active in the area over a long period, so that with the exception of the infilling of the vents the only rocks now exposed are the intrusives.

The red and grey syenites that form the greater part of the Chilwa intrusives occupy a well-defined area about 20 miles in diameter. They are enclosed by alluvium on all sides except on the south, where they intersect representatives of the Nachipere Series. The



THE GEOLOGY OF THE LOWER SHIRE-ZAMBEZI AREA

BY

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latter rocks are traversed by innumerable dolerite dykes of post-Karroo character, but within the outcrop of the syenites no such dykes have been observed; one of these dykes is crossed by a nepheline-bearing intrusive of the Chilwa group. The syenites wholly enclose the limestone of Tundulu Hill, as well as several similar but smaller masses, and reasons have already been given above (p. 55) for regarding this limestone as being of Waterberg age. The Chilwa complex accordingly appears to be of post-Karroo age, and general considerations point to its being older than the main Rift Valley faults; it is therefore very probably contemporaneous with the Lupata outburst. The Pilansberg complex (VII), with which the Chilwa rocks have much in common, is probably of pre-Karroo age.

The Cretaceous beds of the Lower Zambezi have been folded into a gentle N.E.–S.W. syncline intersected by meridional normal faults that are probably related to the Rift Valley movements. Similar faults affect the Tertiary sediments of Sheringoma plateau (VIII).

The Upper Cretaceous and Lower Tertiary marine sediments of the Sheringoma plateau extend northwards to within 25 miles of the Lower Shire-Zambezi confluence (II); they rest upon pebbly sandstones assigned to the Sena Sandstones, but if this correlation is correct either the pebble beds must represent a much higher horizon than that exposed at Sena, or else a stratigraphical break is present.

Tertiary.—The Cretaceous beds at Mutarara and Sena (Fig. 4, Pl. IV) are penetrated by necks of limburgite and olivine-nephelinite (IX, III (7)) that resemble the intrusives intersecting the Inhaminga Grit, of late Tertiary age, that forms the upper beds of Sheringoma plateau (II). Similar intrusives occur also in the Lake Chilwa area and in the Port Herald Hills, and these too are doubtless of late Tertiary age.

Rift Valley Movements and Volcanic Activity.—The distribution of the sediments and lavas of Lupata age is of interest when considered in relation to the development of this part of the Rift Valley, and although the available information is far from complete it points to the following sequence of events. In common with other tracts traversed by the Rift system the area was at first occupied by an elevated plateau, segments of which still form the upper plateaux of Mlanje and Zomba and the Kirk Mountains Plateau; this plateau surface was formed subsequently to the development of the post-Karroo boundary faults. The Rift disturbances began with crustal movements, including probably the formation of ridges and troughs, which led to the subsidence of certain areas, as along the line of the Lower Zambezi and the Lower Shire, and possibly also in the Lake Chilwa region. The Lower Shire-Zambezi area already formed a broad basin owing to the erosion of the Karroo sediments and lavas following upon the elevation of the plateau; into this basin the forerunner of the present Zambezi flowed and assisted in the accumulation of the earlier Lupata sediments. The course of that drainage was probably then as now determined largely by the existence of the Karroo outcrop that traverses the northern part of Southern Rhodesia. The coarseness of these early sediments, which frequently include boulders of gneiss and other rocks ranging up to two feet in length, testifies to the magnitude and the rapid development of the disturbance. Similar conditions prevailed at the northern end of the Nyasan rift valley during the deposition of the Dinosaur Beds (III (4)), which are believed to be for the most part contemporaneous with the Lupata Series. The coarseness of the succeeding Lupata sediments, combined with the unconformities within them and the eroded surface upon which they rest, together indicate the continuance of unstable conditions. Furthermore, the deposition of the sediments was accompanied first by widespread rhyolitic outbursts, and later by the eruption of alkaline lavas and tuffs in more restricted areas, such as the Lower Zambezi and probably also the area south of Lake Chilwa.

The following considerations indicate that here, as in other parts of the Rift Valley, the major rift faulting did not take place until after the accumulation of the Lupata Series. The recent recognition of Lupata Sandstones in the Lower Shire Valley, where locally they probably rest upon earlier Lupata sediments, shows that for a time at least there was communication between the Lower Shire and the Lower Zambezi across the Karroo sediments: but the Lupata beds dip gently eastwards beneath the Shire alluvium, which farther east abuts against the foot of the great Shire Highlands scarp. The Shire Highlands plateau, which overlooks the Lower Shire Valley from a height of fully 3,000 feet, is itself tilted downwards towards the foot of the Mlanje massif and the deeply dissected area immediately to the north on which stand the Chilwa rhyolitic vents. Along the western side of the Port Herald Hills, Lupata rocks dip towards the Zambezi at angles of 6° to 10°, but on the eastern side no trace of these rocks has been observed, and the hills present a steep scarp towards the Lower Shire. Faults of relatively small throw, which none the less amounts to several hundred feet in some cases, intersect the Lupata beds themselves, and on the Sheringoma plateau late Tertiary sediments are also considerably faulted. Farther north, in the Nyasan rift, faulting has taken place intermittently throughout Tertiary and post-Tertiary time (III, (2) (3)).

The Lupata beds of the Lower Zambezi, which only locally and for short distances extend beyond the Karroo outcrop, are folded into a syncline trending northwest-southeast; this syncline is directly superposed upon and possibly related to the preceding somewhat broader faulted syncline of Karroo strata. It is probable that much of this Lupata folding took place shortly after the conclusion of the volcanic episode, for the post-Lupata Sandstones gradually step across the earlier sediments, from which they differ only in the inclusion of abundant pebbles of the alkaline lavas.

The late Cretaceous and Tertiary sediments of Sheringoma are also gently folded, as has been demonstrated by Mennell, but in a direction almost at right angles to the Lupata syncline. The post-Lupata Sandstones dip beneath fossiliferous Upper Cretaceous and Tertiary beds (V (2)) and are folded with them.

The lower Zambezi area evidently continued to subside until late Tertiary times, whereas the Lake Chilwa area was exposed to denudation for much of this period ; for not only have the Chilwa extrusive rocks been entirely removed, but the old land surface has been dissected to the extent of at least 2,000 feet, and the intrusive rocks accompanying the outbursts extensively exposed. This denudation was none the less interrupted by intermittent base-levelling and rift-faulting (III (2) (5)). But since early post-Tertiary times, as a result of down-faulting and interference with the drainage of this part of the rift system (III (5)), the Chilwa area has been aggraded, with the result that the lake itself occupies but a small part of an extensive plain of aggradation out of which rise the roots of the ancient volcanoes.

There is ample evidence that volcanic activity was renewed about the end of the Tertiary, and this was perhaps contemporaneous with that occurring around the northern end of Lake Nyasa (I, III (3)). No extrusive rocks representing this outburst have yet been recognized, but ultrabasic and alkaline intrusions have been observed by Mennell to cut the late Tertiary Inhaminga Grits of the Sheringoma plateau, and similar dykes and volcanic necks are known in the Sena area (Fig. 4, Pl. IV), in the Port Herald Hills, and also around Lake Chilwa.

The structure of Sheringoma plateau shows that about the end of Tertiary times the area was affected by an uplift of more than 1,100 feet. Recent examination of the alluvium of the Zambezi and the Lower Shire proves that subsequently a depression of several hundred feet took place, for near Sena the solid rocks beneath the Zambezi have been scoured out to a maximum depth of fully 150 feet below the present bed of the river (III (10)), and in later times an uplift of at least 90 feet has taken place, as shown by flights of alluvial terraces on the Lower Shire (III (2)). Moreover, in the coast sections north of Beira there is additional evidence of a gentle uplift of recent date.

(*Note.*—Since the above account was written a paper on "Some Mesozoic and Tertiary Igneous Rocks from Portuguese East Africa" has been published (Geol. Mag., LXVI, 1929, pp. 529–40) by F. P. Mennell, who apparently had not seen the paper on the rocks of the Lupata Gorge, by W. Campbell Smith and myself (III (7)), which had appeared a few months earlier. The lens porphyry, lupatite, and leucitophyre of Mr. Mennell's paper seem from the descriptions to correspond to rocks described by us as kenytes; and pseudomorphs which appear to correspond to those attributed to leucite by Mr. Mennell have been shown by us in fresh rocks from the north of the Zambezi to be analcite.—F. D.)

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(2) "The Geology of Portuguese East Africa between the Zambezi and Sabi Rivers," *Trans. Geol. Soc. S. Africa*, xxvi (1923), p. 103.

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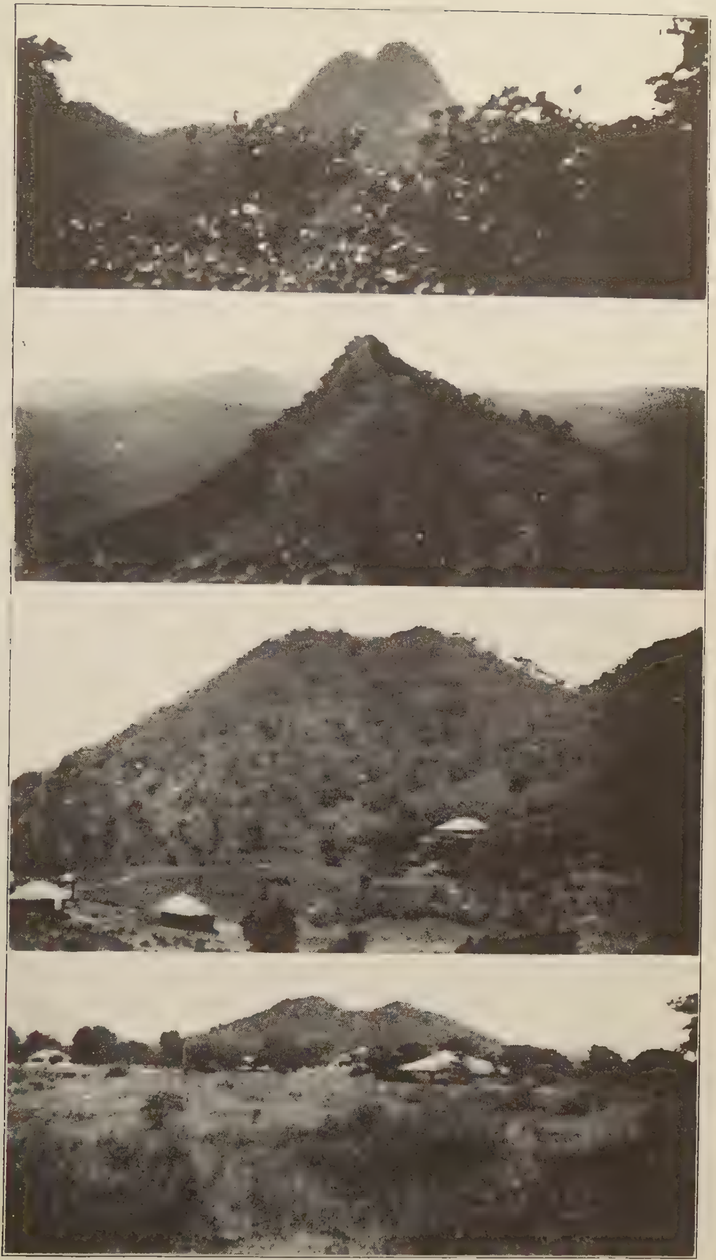
EXPLANATION OF PLATE IV.

FIG. 1.—Domwe Hill, at the southern end of the Port Herald Hills; steeply inclined felspathic quartzite of the Nachipere Series.

FIG. 2.—The eastern end of Nyapanda Ridge, east of Sinjal, as seen from the western end; vertical felspathic quartzite of the Nachipere Series.

FIG. 3.—Malawe Hill, and Boma Rest House, Port Herald Hills; nepheline-syenite intruded into steeply inclined sediments of the Nachipere Series.

FIG. 4.—Sena Hill and Sena, Lower Zambezi; pipes of olivine-nephelinite in Sena Sandstone.



Photographs in Illustration of "The Geology of the Lower Shire-Zambezi Area".

[*To face p.* 60.

The Curve of Stream Erosion.

JOHN CHALLINOR, M.A., F.G.S.

A STUDY of stream action very soon shows that things are by no means so simple as they appear at first sight. Stream erosion is the basis of earth sculpture in temperate regions, except where direct differential weathering carves some of the details; yet its mechanism and the evolution of its topographical effects do not seem to be understood with any certainty. Even the classic discussions by G. K. Gilbert in his *Geology of the Henry Mountains*,[1] and by W. M. Davis in his collected *Geographical Essays*,[2] are, to the present writer at least, unconvincing at those points where the deductive structure is carried over, so to speak, to fit the work of actual streams, particularly with regard to the development of the curves of their longitudinal profiles. The parts given to this subject in the geological and geographical text-books are too short to allow a fully reasoned argument, but all appear to adopt the conclusions of Gilbert and Davis; though the line adopted in the present paper is to some extent approached by Chamberlin and Salisbury.[3]

There is, however, one discussion of erosion curves that does not seem to have received very much attention. This is contained in a work by H. Foster Bain on the "Relations of the Wisconsin and Kansan Drift Sheets in Central Iowa, and Related Phenomena".[4] In trying to straighten out in my own mind the main principles of stream erosion I was led to conclusions that appeared to be unorthodox. I then saw this essay by Bain and was interested to find that the same conclusions were reached by him. His very clear reasoning simplified and clarified my own hitherto somewhat entangled arguments, and encouraged me to formulate more precisely my own ideas in which I thus became more confident. At the same time I also had the advantage of discussing some of these ideas with a mathematical friend and colleague, Mr. W. G. L. Sutton, to whom I am indebted for much valuable suggestion. I should also like to acknowledge the help and encouragement I have received from Dr. Harold Jeffreys, and the benefit derived from frequent discussions with

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[1] G. K. Gilbert, *The Geology of the Henry Mountains*, 1877 (section on "Erosion", pp. 99–114).

[2] W. M. Davis, *Geographical Essays*, edited by D. W. Johnson, 1909; particularly "The Geographical Cycle" (*Geog. Journ.*, vol. xiv, 1899, pp. 481–504) and "Base-level, Grade, and Peneplain" (*Journ. Geol.*, vol. x, 1902, pp. 77–111).

[3] T. C. Chamberlin and R. D. Salisbury, *Geology*, 2nd ed., 1909, vol. i, pp. 57–70. I am indebted to this book for the reference to Bain's work.

[4] H. F. Bain, "Relations of the Wisconsin and Kansan Drift Sheets in Central Iowa, and Related Phenomena" (section on "Analysis of Erosion Curves," pp. 449–58), *Iowa Geol. Survey*, vol. vi, pp. 433–76.

Professor W. J. Pugh. I am fully conscious that there are many imperfections in my treatment of this intricate subject, although I believe the general argument to be sound. These imperfections are partly a question of space; others must be put down to pure ignorance. In any case, I am alone responsible for them.

It is first of all necessary to postulate a few fundamental assumptions, as follows:—

1. The quantity of water passing in unit time through any cross-section of a stream is the product of area of cross-section of water and velocity. This quantity is a fundamental datum.
2. If there is no external addition of water to the stream, the quantity of water passing through each and every cross-section in a given time is the same.
3. An increase in slope increases the velocity but proportionately decreases the area of cross-section.
4. The possible amount of mechanical load varies with the quantity of water.
5. The possible corrasion varies, in the first place, with the possible load.
6. Increase in slope, by leaving the quantity of water unchanged, does not affect the possible load.
7. Increase in slope, by increasing the velocity, increases the size of the largest transportable particle of load.
8. Increase in slope, by increasing the velocity, increases the possible corrasion.
9. Increase in quantity of water increases both the area of cross-section and the velocity.
10. Increase in quantity of water increases the possible load (4), and thus possible corrasion (5), and by the resulting increase in velocity further increases the possible corrasion.
11. For a given quantity of water and a given slope, velocity varies inversely with the actual load transported.
12. A stream is always fully loaded; in the sense that it can carry no more load without loss of velocity.
13. A stream is never fully loaded; in the sense that it can always carry more load if the load is composed of finer particles.
14. The continued addition of load of ever finer and finer particles allows the stream to carry a load approaching the maximum, or possible, load for that quantity of water; and the velocity decreases, eventually becoming very small. At the same time, the area of cross-section increases, as the quantity of water is not affected by the addition of load.

In putting these assumptions as dogmatic statements, for the sake of being definite, it is not meant to suggest that they are necessarily laws. After corroboration or modification by mathematical scrutiny, or by observation and experiment, they might be found to attain that status. Some of them are obvious, others are not. Also, some of them are stated or implied in the books and thers are not. The entire dependence of possible load (the meaning f which is stated in assumption 14) on quantity of water is not ery certain. Velocity is one of the measures of quantity, but the ossible load might depend in addition on the velocity the stream ould have, supposing it to have no load; that is, possible load night increase with quantity in more than a simple ratio, because ncrease in quantity means increase in velocity; and, independently, he possible load might increase with slope (assumption (6) would hen be untrue). Should this be so, the increase of corrasion with uantity and with slope would be all the greater. By possible orrasion is meant corrasion apart from deposition. In assumption (5) t is stated that this varies with the possible load; but probably his is only true as a first approximation—with continued increase n load as visualized in assumption (14), the rate of corresponding ncrease in possible corrasion would very likely fall off. Assumption 9) merely states the well-known fact that after a storm a stream ecomes both deeper and swifter.

I am intentionally omitting such questions as the relation between uantity of water and velocity on the one hand and amount and izes of actual (as distinct from possible) load on the other, and the nethods of transport of the various sizes of load particles. A study f the exact mechanism of corrasion and deposition—a study not ere attempted—would have to take account of these.

The assumptions are not all used directly in arriving at the onclusions about profile-curves, but they all seem likely to bear n the matter.

The line of reasoning about the initiation and development of he longitudinal profile-curves of rivers may be started by taking considerable portion of an ideal river flowing down a uniform slope ver a uniform rock, and increasing in quantity from its upper o its lower reaches. Assumption (4) states that increase in quantity ncreases possible corrasion, therefore (unless for some reason the ctual corrasion does not keep pace with the possible corrasion, nd there seems no reason why it should not), at the end of any eriod of time, there will be an increase, as we proceed downstream, n the depth by which the bed has been lowered.

The slope as a whole will have increased in amount but may ave become concave or convex or have remained a straight line, ccording as to whether the increase in corrasion has been less than, r more than, or exactly in simple proportion to the increase in he length of the stream from the starting point. In the ideal case as in all normal actual cases) the rate of increase in corrasion will ecome continually greater as we go downstream, because the river ncreases in size (quantity of water) by ever greater and greater mounts, for the same distances along its course. This latter fact nay be explained as follows :—If the river received no tributaries he increase in volume would be uniform as, supposing the rain to all equally along the line of flow and ignoring evaporation, the quantity of water passing any point would be the sum of all that has fallen above. But as the river normally receives tributaries, it is continually adding to this simple increase. The tributaries may keep much the same in number for the same length of the main river, but will include amongst this number tributaries of ever larger and larger size, so that the additional increase to the waters of the main river is by ever greater and greater amounts.

The uniform slope thus tends to be altered to one that is *convex upwards* (or simply " convex ").

It is often argued that a river, flowing originally down a uniform slope, will tend to produce a profile curve that is concave from the start of its development, on the ground that there is very little load to cause corrasion in the uppermost reaches while in the lower reaches there is so much load that corrasion is balanced by deposition, so that corrasion is at a maximum in some intermediate reach, falling off both above and below. However, it seems at least nearer the truth to assume that the corrasion by the river increases downstream in the manner just outlined.

This fundamental tendency towards convexity is cumulative; just as the opposite tendency, that towards concavity, would be cumulative if once started throughout. Directly the convex curve has been initiated there is increased slope as well as increased quantity of water as we go downstream. The effect of increased slope (8) is added to that of increased quantity of water, and the convex curve becomes more and more accentuated, and more and more quickly so, as it is developed.

We now have conditions of which the further evolution has been demonstrated by Bain. He arrives at the condition of convexity by starting, not with a uniform slope, but a block of country with flat top and vertical sides, and allowing weathering, sheet-erosion and stream erosion (" stream action may be considered as merely a special case of sheet erosion," as he remarks) to act, in the first place, along a horizontal edge. This theoretical assumption is, of course, just as valid as that of a uniform slope, and it is significant that they both lead to the same result.

But the longitudinal profile curve of rivers in general is conspicuously concave. This is due to the fact that the tendency to produce a convex curve is interfered with, and finally more or less completely masked, by the effects of base-level.

Base-level may be defined as a limiting level below which a river cannot cut down, and is most completely realized in sea-level, this being the ultimate, constant and " permanent " base-level of all rivers which reach the sea. Such a level is, however, only permanent in the absence of earth movements. All rivers, at least in temperate regions, do reach the sea in the sense that their waters reach the sea; but a tributary stream may be considered as ending where it reaches the river into which it flows. The base-level of a tributary stream is the level of the main stream at the point of confluence, and this level is continually being lowered. But at any one moment such a base-level is the "ultimate" one to which the tributary is working. Thirdly, all rivers may (and usually do) develop temporary base-levels by the occurrence of obstacles, such as a specially resistant rock, and these levels may be of greater or less stability. When lakes are produced by such obstacles (or otherwise) such levels are relatively stable, but to the other extreme they graduate into parts of the stream's course where the rate of downward cutting is only slightly held up; and the base-level (the term being now hardly merited) is lowered nearly as fast as the stream itself would be. The stream above is merely checked in its rate of downward cutting, and never has time to develop a curve in even approximate equilibrium with the "base-level" of the moment. But the idea and effect of base-level is still present in the hindrance to vertical corrasion produced by such irregularities; and we may say that the longitudinal profiles of all streams are entirely due to the restrictive effects of the base-levels which exist, or have existed, super-imposed on a curve which, if it were not for the base-levels, would be convex. A stream not working to a base-level has a convex profile.

Suppose, then, the river flowing down a uniform slope which ends in the sea. In the manner and for the reasons indicated above, the river tends to produce a profile which is convex. As both the quantity of water and its velocity increase downstream, there will be no deposition on the river bed so long as the convexity remains. When the river reaches base-level at the sea the velocity is suddenly checked and all but the very finest load will be suddenly dropped at the mouth. The sea will at once begin to deal with this material, and will continually be removing some of it. The conditions are essentially those discussed by Bain and, as he shows, a concave curve due to the condition of base-level (he does not mention this term, however), initiated by deposition alone, and at once modified by erosion and further deposition, will be formed and develop and gain at the expense of the convexity. In his words: "The concave portion once established tends to perpetuate itself and the relative insignificance of the convex curve at the head of the stream causes it to be overlooked." At the same time the whole profile will approach more and more nearly to base-level. Bain makes the ultimate line reached one that has a small and rather definite slope seawards, but this does not seem to be theoretically necessary.

To recapitulate the evolution of this profile: suppose it to begin as an inclined straight line, a convex curve is at once started throughout, and tends to become more accentuated; at the same time a concave curve is started at the point of base-level (the mouth of the river) and rapidly develops in accentuation and size, moving upstream and eliminating the convexity as it goes. As it is lowered the profile becomes flatter and flatter, so that the concavity (while nevertheless still continuing to increase its hold upon the form of the profile) becomes less and less pronounced. As all parts of the profile now become less and less steep, the action in general, and vertical corrasion in particular, is slowed up. The limit—the horizontal line at base-level—is all the time and everywhere being approached, but more and more slowly the more nearly it is attained. Given an absolutely stable base-level (i.e. absence of earth-movements) it would be reached theoretically by the river after an infinite time, and, at the last, infinitely slowly.

I wish to emphasize the idea of the continuity of this evolution. There appears to be no point in the process when any particular stability is attained, although as the evolution proceeds the profile becomes more and more stable in the sense that potential change in it becomes less and actual change slower. But it is usually assumed, on the principle of the " grading " of the profile, that a river can only continue to approach base-level—and the fact that it does so is recognized—by a gradual change in the character of the load, or in the climate, or in some " accidental " alteration of the slope. It does not appear that this is at all necessary. It is not, however, suggested that there is any theoretical fallacy in the idea of the " grading " of a short portion of a river bed.[1]

Incidentally, a natural explanation of river terraces as a normal (in fact, almost inevitable) phenomenon of river valleys also follows. Deposition will occur *in excess of erosion* along those concave parts of the profile where the rate of change of slope is sufficiently great. The uppermost reaches of the flattened lower part of the profile will in general be such. These reaches of excessive deposition will migrate upstream as the profile develops, and along the parts of the profile below them the river will again degrade its aggraded valley. In these parts (where not too near base-level) conditions will be particularly favourable for the production of typical river terraces by the meandering river.

We may now note what happens to a river, particularly its profile, near the source. It has been seen that the concave curve develops and moves upstream. It is the upstream part in particular of this curve that moves upstream, and, unless the convexity can retreat as a whole, it at the same time tends to become steeper and steeper. Finally we have the river with a short, slightly convex profile near the source plunging down a steep slope at the foot of which the slope rapidly falls off. As this slope increases in steepness and approaches the original source, by a combined process of undermining and assimilation of adjacent drainage the source itself is gradually pushed back. The source cannot begin to recede until the development of the concavity, both as regards degree and position, has reached its limit. The river will still tend to keep a slight convexity near the source ; the steep slope of the concave curve, the top of which must be considered as belonging also to the convex curve, cannot in normal cases begin at the actual source. If the land slopes progressively upwards, then the source will rise higher and higher as it recedes. But in actual cases it must soon reach the watershed ; in fact, in the ideal case it would be at the watershed, and the lengthening of the river (the pushing back of the source) would mean the source being lowered as it gradually descended the opposite side of the watershed. Streams flowing in the opposite direction to this stream (and to those flowing parallel to it) may also push back their sources, so that the whole watershed becomes lowered, and from being a straight line becomes zig-zag. Usually the conditions which govern the vigour of the rivers are not equally distributed on each side of the watershed, so that the rivers flowing down one side gain at the expense of the others, and the watershed is pushed backwards in one direction, as well as lowered. Streams which are shortening by the capture of their headwaters will have abnormal features at their sources.

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[1] The clearest explanation that I know of this principle is given by P. Lake, *Physical Geography*, 1919, pp. 235–37.

Thus the whole profile of the river is lowered from and including the source to (but not including) the mouth. It will be seen that we can imagine the initial ideal river as being quite short and flowing down some " ready made " slope into the sea, and gradually pushing its headwaters back into the country.

To examine the character of the source :—It may first be thought of as being a minute channel of just sufficient definition to collect water in it and direct the flow along it. In a climate of varying rainfall, as all climates are, the position of the source would vary ; when little rain, the channel would have to be large enough to have tapped a sufficiently large area of general flow, or to have assimilated a sufficient number of tributary channels with more or less tendency to contain " rills ". Actually, a river generally begins as a spring, i.e. the source has at least a certain degree of permanency. But the spring is not strictly the ultimate potential source of a stream, as its presence implies higher land above ; and higher land above implies power of water to flow over it. In addition to allowing water to flow over it, the land above a spring acts as a sponge. This is markedly the case if there is a difference in the permeability of the rock above and below the spring ; such a difference of course often determines the presence and position of well-marked springs. For theoretical purposes, the stream's course should be considered as extending as far above a spring as water ever flows into it over-ground, i.e. normally to the top of the watershed. The spring is equivalent to the accession by the river of a relatively very large tributary (larger than itself).

But it is the evolution of the entire profile as a unit which is of primary importance. The object of the foregoing discussion is to suggest that this evolution, indeed, the whole question of river action, is in need of re-examination.

On the Chronological Order of Deposition of the Highland Schists.[1]

By Thorolf Vogt, Professor of Geology, Trondhjem.

(PLATE V.)

As is well known, the chronological order of deposition of the sediments of that broad band of schists which extends across Scotland from Banffshire and Aberdeenshire in the north-east to Argyllshire in the south-west is a most difficult problem to determine. The noteworthy development that has been made during recent years, leading to a more intimate understanding of the structure of the Southern Highlands, has made this problem much more vital. The question as to the top and bottom of these beds has been much discussed in recent years, and it can not be denied that views have been widely divergent on this matter. When a foreign geologist desires to call attention (through this paper) to certain conditions of fact, it may be pointed out that he is carrying on similar studies of another section—the Norwegian—of this same mountain chain, where one meets similar problems as in the Scottish Highlands.

Where the structure is so complicated that it is difficult to determine the chronological order of deposition from the structural sequence, one must resort to other criteria in the beds themselves, assuming that fossiliferous key-beds are absent. A well-known example from the thrust region of the North-West Highlands is cited in Peach and Horne's classical monograph on this region: at Loch Eireboll, Murchison assumed the existence of an upper quartzite horizon which Nicol showed to be an inversion of the usual Cambrian quartzite, inasmuch as the trumpet-shaped openings of the '"pipes" were found to be on the lower faces, a condition which indicated a complete reversal of the beds. We have a second example from the Highland Schists themselves whereby Bailey's Loch Awe map was oriented. Dr. Peach examined the Dalradian Tayvallich lava on the Knapdale peninsula and found the pipe-amygdales springing from the base, while the upper portion of the lava was wholly slaggy. In later years E. B. Bailey, G. Barrow, and E. M. Anderson have made numerous applications of the principle of local unconformities with contemporaneous erosion, though in part with conflicting results.

The region where the observations under discussion were made is at Ballachulish, which has been described in great detail by E. B. Bailey[2] and is of such great interest to students of structural

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[1] E. B. Bailey accepts T. Vogt's reinterpretation of the Ballachulish succession, and discusses the consequences in a later paper in this number of the Geol. Mag.—Editor.

[2] E. B. Bailey, "Recumbent Folds in the Schists of the Scottish Highlands," *Q.J.G.S.*, vol. lxvi, pp. 586–618, 1910; E. B. Bailey, H. B. Maufe, and others, "The Geology of Ben Nevis and Glencoe," Expl. of Sheet 53, *Mem. Geol. Surv. Scotland*, 1916; E. B. Bailey, "The Structure of the South-West Highlands of Scotland," *Q.J.G.S.*, vol. lxxviii, pp. 82–127, 1922.

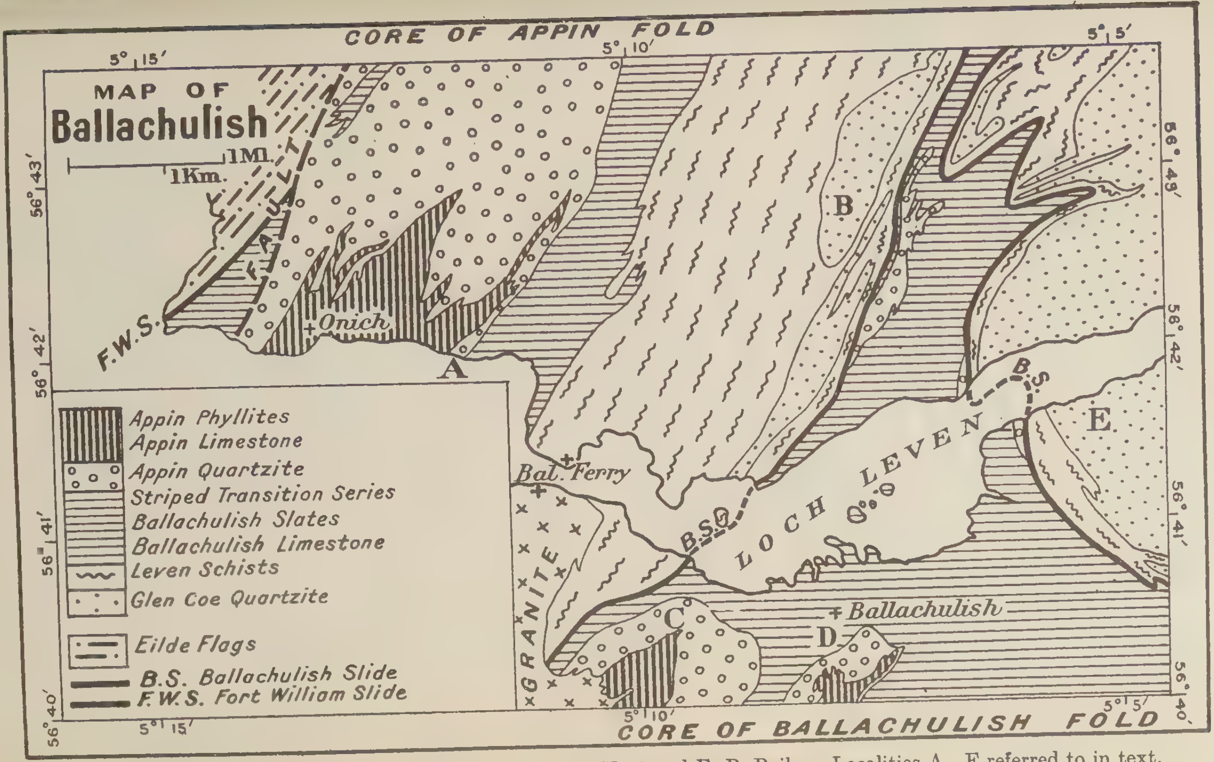

Fig. 1.—Map of Ballachulish to illustrate papers by T. Vogt and E. B. Bailey. Localities A—E referred to in text.

geology. Heretofore no criterion has been known by which the top and bottom of the beds in this region—the Ballappel formation, including the Appin and Ballachulish nappes—could be determined. Bailey has left this question open in his earlier papers, as in the case of the other sediments of the district. In his latest paper, however, he draws a parallel between the above mentioned series and the Iltay and Loch Awe nappes, and thus establishes a basis for orientation of the top and bottom of the beds. It should be mentioned though that there exists a controversy of opinion with H. H. Read,[1] who undertakes correlation with the Ballachulish series, but in inverse order.

When the writer visited the Ballachulish district during the summer of 1924 in company with Mr. Sherwood Buckstaff and Mr. Olaf N. Rove from the University of Wisconsin, we discussed the question of the top and bottom of the beds. The series contains two quartzites, the Glencoe Quartzite and the Appin Quartzite, both of which Bailey (1910, p. 596 and 599) describes as being cross-bedded. We felt that here we had the key to the solution of the problem.

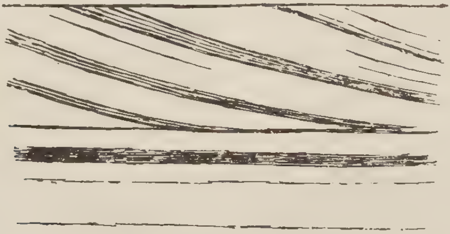

Fig. 2.—Cross-bedding from Glen Coe quartzite on Tom Meadhoin (*B*, Fig. 1) ; about one-fifth natural size.

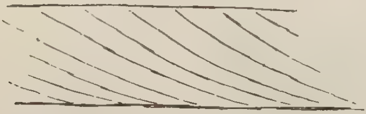

Fig. 3.—Cross-bedding from Glen Coe quartzite on Tom Meadhoin (*B*, Fig. 1) ; about one-fifth natural size.

We first found cross-bedding in the Glencoe quartzite on Tom Meadhoin (*B* of Fig. 1) of a normal delta type laid down in standing water. In curved cross-bedding it is well known that the top of the foreset bed is concave upward ; the foreset beds meet the topset beds in an angle or in an abrupt curve, and they merge with the bottom sets in a broader curve. As one walks east along the highest part of the ridge one comes upon the Glencoe quartzite well exposed and clearly structurally underlying the Leven schists, which have a variable dip from 25° to 60° or more. Cross-bedding is relatively common (though not always clearly developed) from near the boundary with the Leven schists and eastwards. The cross-bedding could be seen on the weathered surface of steep fractures as alternating light and dark bands. Two drawings (Figs. 2 and 3) show the character of the cross-bedding, and its appearance is indicated in the photograph (Pl. V, Fig. 1). This illustration is an enlargement of a picture taken by Mr. Buckstaff with a pocket camera. (It was raining at the time the picture was taken.) The cross-bedding on Tom Meadhoin shows that the structural sequence in this case corresponds to the original sequence of deposition, and hence the Leven schists are really underlain stratigraphically by the Glencoe quartzite.

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[1] H. H. Read, "The Geology of the Country around Banff, Huntly, and Turriff," Expl. of Sheets 86 and 96, *Mem. Geol. Surv. Scotland*, 1923 ; H. H. Read, *Q.J.G.S.*, vol. lxxviii, pp. 129–30, 1922.

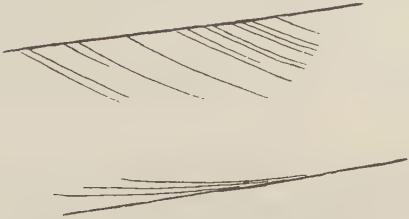


Fig. 4.—Cross-bedding from Appin Quartzite at Loch Leven (*A*, Fig. 1); about one-third natural size.

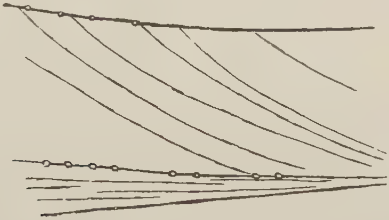


Fig. 5.—Cross-bedding from Appin Quartzite at Loch Leven (*A*, Fig. 1); with layers of quartz pebbles; about one-tenth natural size.

The next day we spent some hours along the Onich shore (*A*, Fig. 1), west of the church near Loch Leven Hotel, in looking for cross-bedding in the Appin quartzite. The cross-bedding is here seen as thin red stripes on the steeply dipping fractures of the white quartzite. This structure is visible only, or best, at low water. The best structures are seen just below the Stewart Monument, where there may also be seen thin rows of small quartz-pebbles in the quartzite. Figs. 4 and 5 are drawings of the quartzite as seen here. We observed that the grain-size of one of the curved lamellae was largest towards the convex part of the strata and gradually decreased toward the concave surface, a condition which, as is well known, supplements the observation of the cross-bedding itself.

This exposure of cross-bedding indicates that the beds are inverted toward the west, and that the Appin quartzite lies stratigraphically above the Ballachulish slates and below the Appin limestone.

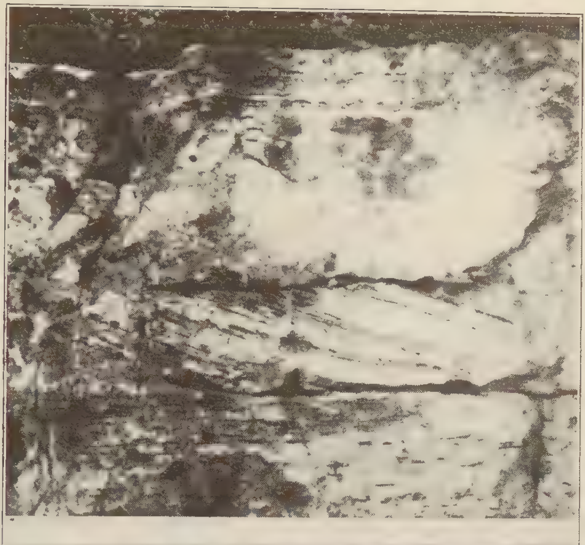
In a small quartzite layer just west of the first exposure of the Appin limestone above the main quartzite, cross-bedding was observed to indicate that the top of the beds faces east ; the opposite to the conditions in the main quartzite. This indicates that this small quartzite layer is an " infolded " part of the main quartzite, just as Bailey has indicated in his sections.

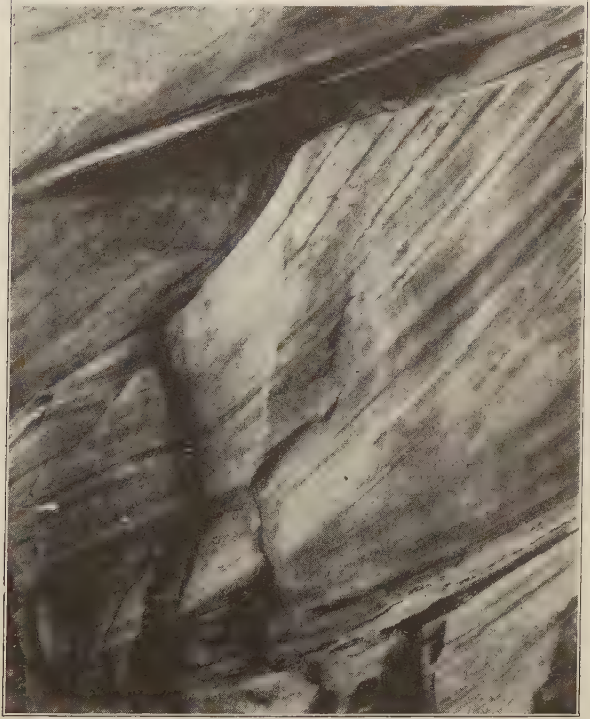
The localities with Glencoe and Appin quartzite lie in a continuous succession without a tectonic break (see particularly Bailey's section on p. 80, *Memoir* 53), and in both places the observations confirm the top and bottom of the formation. The writer believes that those who are familiar with cross-bedding will at once realize that these observations orient the stratigraphic sequence, which is then as follows :—

Appin phyllites (top).
Appin limestone.
Appin quartzite.
Ballachulish slates.
Ballachulish limestone.
Leven schists.
Glencoe quartzite (bottom).

This chronological order of sequence implies certain consequences in the tectonic structure, that is, the direction of application of the folding force. Without going into detail here, one must come to the conclusion that the thrust has been applied from the south-east, in the same direction as in the near-by great thrust region of the North-west Highlands.

It is the writer's opinion that a further investigation over a wide area along the lines suggested above might lead to interesting results, in that the cross-bedding might serve as a clue to the disentangling of the chronological sequence of the Highland schists. A minimum of results must be expected in the most metamorphosed regions, where primary structure, if at one time present, may well have been obliterated during the recrystallization of the rocks. On the other hand, there should be good opportunities in areas of little metamorphism, such as large portions of the South-west Highlands, and in the area along the great Highland border fault-line ; areas which are indicated on Bailey's and Barrow's maps of the metamorphosed regions.





CROSS-BEDDING IN SANDSTONES.

FIG. 1.—GLEN COE QUARTZITE, TOM MEADHOIN. (*See* T. Vogt.)

FIG. 2.—GASPÉ, CANADA. (*See* T. L. Tanton.)

[*To face p.* 72.

In closing, the writer wishes to express his appreciation and thanks to the members of the Geological Survey fo Scotland for their courtesy and co-operation during his visit. Special thanks are due to Mr. E. B. Bailey for planning the writer's trip to the South-west Highlands, and to Dr. Horne for planning a trip to the North-west Highlands.

KRISTIANIA.
December, 1924.

Determination of Age-Relations in Folded Rocks.

By T. L. TANTON, Canadian Geological Survey.

(PLATES V, VI and VII.)

INTRODUCTION.

DURING the summer of 1929 members of the International Summer School of Geology and Natural Resources, Princeton University, had the opportunity of examining with Mr. E. B. Bailey geological sections in the South-west highlands of Scotland and assisting in the determinations of tops and bottoms of beds in certain critical areas. The subdivision of the series into formations and the distribution of these formations were already for the most part known, but some important details of the structural interpretation were in doubt. In 1924, Thorolf Vogt, after visiting the area, stated that he had determined the order of succession in parts of the folded series; but these determinations by Vogt and their implications had not been verified or accepted by Mr. Bailey by the early part of 1929. Detailed observations made by the Princeton party in 1929, on strata which admitted of top and bottom determinations on the basis of cross-bedding, channelling and texture gradations, confirmed and extended the findings of Vogt; and Mr. Bailey is now in a position to restate the structural interpretation of the South-west Highlands making use of satisfactorily determined sequences in some of the units where formerly the sequence was in doubt or had been incorrectly inferred.

The writer's contribution to the clarification of the structural interpretation of the South-west Highlands consisted in the recognition of phenomena of various kinds, both primary and secondary structures, which appeared to him to furnish the basis for top and bottom determinations and. in stimulating the search for primary structures of recognized diagnostic value. In some outcrops confirmatory evidence from several kinds of clues was possible and in some exposures, where doubts might have been reasonably entertained as to the interpretation of e.g. rather obscure channellings and texture-gradations, other structures could be found in such development as to dispel all doubt. As a result of the Princeton party's examination it appeared desirable to Mr. Bailey that, before announcing the revised interpretation of the South-west Highlands, a statement should be made calling attention to the various criteria admitting of top and bottom determinations, condensed in a manner such as has not been hitherto conveniently available.

In compliance with Mr. Bailey's request, I have assembled a guide to the diagnostic phenomena and their interpretation. My familiarity with the interpretation of the phenomena commenced with demonstrations and instruction given by Dr. C. K. Leith. A comprehensive treatment of the subject is contained in text books by C. K. Leith[1] and W. H. Twenhofel[2] of the University of Wisconsin.

The following primary structures indicate the tops and bottoms of the beds in which they occur and hence they are of value in interpreting the order of succession in highly folded, non-fossiliferous strata.

Cross-bedding or False-bedding.[3]—The false-bedding is sharply truncated by overlying layers. It comes in contact with underlying layers by a tangential curve.

Plate V, Fig. 2, photo by E. M. Kindle, G.S. Canada, 11th January, 1929; and C. K. Leith, p. 188.

Where parts of false-bedded lenses have been truncated the concave false-bedding is toward the original upper side.

Plate V, Fig. 2, photo E. M. Kindle, G.S. Canada, 11th January, 1929.

Channelling.—The concave sides of erosion-channels are toward the original upper side. The edges of beds truncated by erosion are toward the original top.

Mud Cracks.—When viewed at right angles to the stratification, mud cracks decrease in width toward the original lower side.

Texture Gradations.—In beds of composite texture where there is a gradation from a coarse-textured sediment at one side to a relatively fine-grained sediment at the other, the finer-grained material is toward the original upper side. It has been frequently observed in the Precambrian of the Canadian Shield that beds of composite texture are associated in groups like varves. The interpretation of the original direction of the top side is considered satisfactory when in each bed the change from coarse to fine is in the same direction.

Plate VI, photo T. L. Tanton, G.S. Canada, 65024.

Pebble Dints.—In certain conglomerates, pebbles occur in a matrix of distinctly stratified fine-grained material. When the layering in the matrix is bulged around a pebble at one side only it is to be inferred that this side of the pebble is toward the original lower side and that the bulge is a dint or sag caused by the weight of the pebble.[1]

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[1] C. K. Leith, *Structural Geology* (Henry Holt and Co., 1923).

[2] Wm. H. Twenhofel, *Treatise on Sedimentation* (The Williams and Wilkins Co., Baltimore, 1926).

[3] [I prefer to use false-bedding as a generic term including current-bedding and slip-bedding. The remarks in the text refer to current-bedding.—E. B. BAILEY.]

Ripple Marks.—The crests of ripple marks, of the symmetrical type, are sharper than the troughs. The troughs may have minor crests in them.[2]

Tops of Lava-flows.—The tops of lava-flows are usually more vesicular than their lower part.

The elongation of pipe amygdules is in a direction which was originally vertical when the flow solidified. Due to the flow slope, this direction is not always at right angles to the surface of the bed. In amygdaloidal lavas which contain branching tubules, the direction of branching is toward the original bottom, the direction of junction is toward the original top.[3]

Flow Wrinkles.—The crests of flowage wrinkles on the surfaces of beds of mudstone or lava are more smoothly curved than the depressions between the wrinkles. The ability to distinguish between the wrinkled surface itself and the cast admits of determining the original top and bottom.

Plate VII, Fig. 1, photo T. L. Tanton, G.S. Canada, 48376 (flow wrinkles on basaltic lava of late Precambrian age, Wilson Island, Lake Superior).

Pillow Lavas.—In some pillow lavas it has been observed that one side of each individual pillow and particularly the larger pillows is less convex than the other parts of the boundary, thus giving to each such pillow the shape of a bun. The interpretation of the bun structure is that the relatively flat surface is toward the original bottom.[4]

The following secondary structures in folded rocks admit of interpretations of tops and bottoms of layers, which have not been refolded after inversion.

Curved Fracture Cleavage such as Occurs in Deformed Beds of Composite Texture.—In the coarser-textured part of beds of composite texture the fracture-cleavage makes a greater acute angle with the bedding than in the finer grained part of the same bed. The convex side of the curvature of the fracture-cleavage is toward the original top. In some cases the curved fracture-cleavage is more readily observable than the gradational texture variation itself.[5]

It is impossible to fold a series of layers whether of paper or rock without causing a slipping between them. In an anticline the upper beds move over the lower beds toward the anticlinal axis ; in a syncline the lower beds move under higher beds toward the synclinal axis. In the case of rocks there is not only movement between the beds but also a similar movement within the beds. In a series made up of beds of different degrees of competence the evidences of movements are more conspicuous in the weaker beds, and the various induced structures which record the directions of relative movement between the beds and different parts of individual beds are flow-cleavage, fracture-cleavage or jointing, and drag-folds.

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[1] For photograph illustrating texture gradations and pebble dints, see W. H. Collins, *G.S. Canada Mem.* 33, pl. iii, fig. 1, p. 84 (1913).

[2] C. K. Leith, p. 186.

[3] W. E. Logan, *Geology of Canada*, 1863, p. 71.

[4] *G.S. Canada, Mem.* 39, plate xl (1913).

[5] *Trans. Roy. Soc. Canada*, 3rd ser., vol. xx, sec. iv, p. 45 (1926).

Drag Folds.—As viewed in the field, drag-folds are of two types, either shaped like an S or the mirror image of this letter. The directions of relative movement involved in the development of these structures have been determined experimentally; in the case of a drag-fold as here represented by the letter S the movement of the material above the S has been left relative to the material below. This observation, together with the foregoing generalization regarding the movement in folded beds, affords a means of determining tops and bottoms of beds.

If in an isolated outcrop of vertical beds it is apparent from the drag-folds that, e.g. the left-hand side has moved up relatively to the right-hand side, it is to be inferred that the outcrop forms part of the left limb of an anticline and hence the original top of the beds is toward the left.[1]

Flow Cleavage.—Flow cleavage develops parallel to the axial planes of both minor and major folds. It is inclined to the bedding and its inclination varies in direction and degree in different parts of the folds. The angular relations of bedding and flow cleavage are known and the observation of the angular relations in outcrops shows in what part of the fold the observation is taken, the direction of movement between and within beds, and hence the tops and bottoms of the beds. For example, if east-west vertical bedding is crossed by a flow-cleavage dipping north the interpretation is that the beds on the south moved relatively upward with reference to those on the north; that a synclinal axis lies to the south; and that the original top of the beds is towards the south.[2]

Fracture Cleavage.—Differential movement between beds develops two sets of shearing planes, one parallel to the bedding, the other inclined and more nearly parallel to the axial plane of the fold than to the bedding. Joints or fracture cleavage form along these planes. The set of fracture-cleavage planes which are inclined to the bedding occur in definite angular relationship to the bedding and interpretations can be made similar to those obtained from flow cleavage. For example, if east-west vertical bedding is crossed by fracture-cleavage dipping north the interpretation is that the beds on the south moved relatively upward with reference to those on the north and that the original top of the beds is toward the south.

Plate VI, photo T. L. Tanton, G.S. Canada, 65024.

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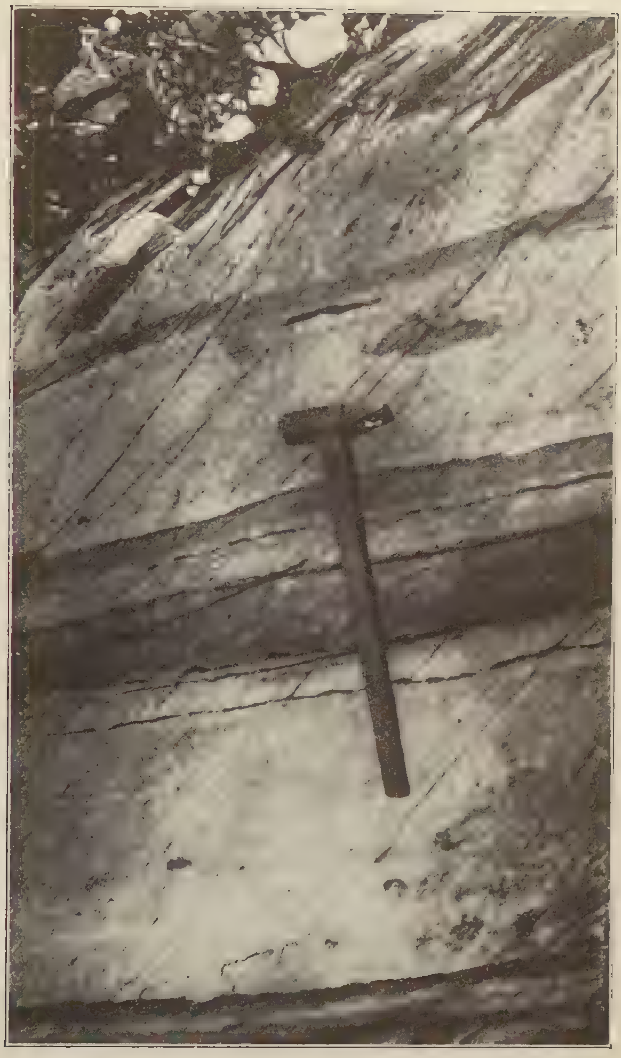
[1] C. K. Leith, p. 177.
[2] C. K. Leith, p. 127.



Horizontal surface on vertically dipping beds of composite texture, Steeprock, Lake Ontario. The gradations from coarse to fine indicate the tops are toward the hammer head, this is also indicated in the curved fracture cleavage. The angular relations between the fracture cleavage and the bedding indicate the direction of relative movement between the beds, each higher bed moved with reference to the adjacent lower (stratigraphic) bed in the direction pointed by the chisel end of the hammer head, and an anticlinal axis lies in the direction pointed by the handle away from the hammer head. (*See* T. L. Tanton.)

[*To face p.* 76.

New Light on Sedimentation and Tectonics.

By E. B. Bailey, M.C., M.A.

(PLATE VII.)

IN the present number of this Magazine (p. 68) Thorolf Vogt has furnished one of the most important and welcome contributions that has ever been made to the interpretation of the Scottish Highlands. The date 1924 stands at the foot of his brief note, and shows that there has been a serious delay in its publication. After explaining this delay, I propose to introduce certain new ideas which have followed in the wake of Vogt's discovery.

Vogt visited the Ballachulish district in the summer of 1924 accompanied by S. Buckstaff and O. N. Rove. He soon wrote to tell me that his little party had not had time to form an opinion as to whether my great recumbent folds and slides[1] were realities, but that it was certain that my original order of succession as put forward in 1922 was the reverse of the truth. He indicated that this conclusion was based on the form of current bedding observable in the Glen Coe quartzite at Tom Meadhoin (Plate V, Fig. 1, p. 72; *B*, Map, p. 69), but otherwise did not enter into details. I replied that I hoped he would soon publish his observations so that Scottish geologists might follow up the matter. At the same time I felt that reliance had perhaps been placed upon some insufficient clue; and, as time passed and no paper appeared, I did not write again to press for publication. Instead, I discussed the matter with my Scottish friends and tried to gain education upon current bedding as an indication of original order of succession. Progress was nil for a long time; but fresh hope arose when, in 1927, R. M. Field invited me to join the Princeton Summer School in an excursion across Canada. American geologists have paid particular attention to criteria of original order of succession (cf. T. L. Tanton, 1930, p. 73) and I tried my best to learn their views on the matter.

Two main criteria of original order of superposition came up for discussion during our traverse of Canada: the one depends upon what may be termed *graded bedding* and the other upon *current bedding*. Both types of bedding belong to arenaceous sediments, but in Canada as in Britain they are as a rule exhibited separately, not in conjunction. That is, one set of arenaceous deposits exhibits graded bedding and another current bedding, but no sandstone that I have seen shows both graded and current bedding. Unfortunately, I did not in 1927 realize the significance of this exclusion. Accordingly, as graded bedding seemed to give absolutely certain results, while current bedding sometimes appeared ambiguous, I fastened upon graded bedding as likely to furnish a sure key to the Ballachulish and other Highland successions. I defer for a moment any definition of graded bedding, for on my return to Scotland I found it of no assistance in reading the Ballachulish riddle.

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[1] *Slide* is a general term for fold-fault. A slide which diminishes or replaces an *inverted* fold-limb, real or virtual is called a *thrust*. A slide which diminishes or replaces an *uninverted* (normal) fold-limb is called a *lag*.

Here let me explain why it took me so long to reach certainty in regard to the value of current bedding. There is a tendency for its exponents to state over briefly that the concavities of current bedding originally face upwards. This can again and again be seen to be untrue. For instance, in mounds of glacial sand and gravel, it is extremely common to find marked concavities of current bedding facing downwards. The curve *ABCD* of Fig. 1 is representative of what may be called the *complete* current-bedded form as seen in a section of a composite bed, the base of which is *LM* and the top *NO*. This complete form has a downwardly directed concavity at *B* and an upwardly directed concavity at *C*. It does not in itself provide any criteria of original order of deposition. Fortunately, however, penecontemporaneous erosion very often removes the concavity at *B*, while sparing that at *C*. As a result the upper surface of the composite bed is cut away to *PQ* and the remaining portion of the current-bedding curve *CD* has a truncated top contrasting with an asymptotic base (*cf.* the illustrations of Vogt's and Tanton's papers). I did not fully realize this simple and convincing story until Field brought the Princeton Summer School to Scotland during the past summer, 1929.

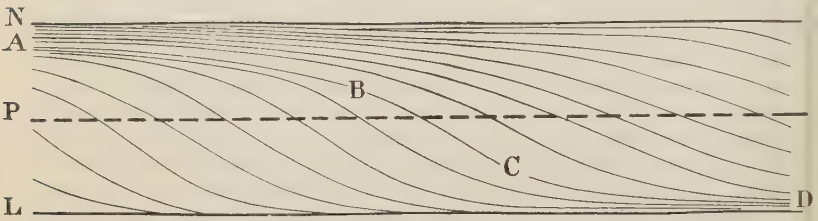

Fig. 1.—A complete composite current bed, with top at *NO*, is often reduced by penecontemporaneous erosion to an incomplete composite current bed, with top at *PQ*. This commonly leads to obvious truncation of the remaining portions of the curved current laminae.

In 1928, however, Vogt's contention received very considerable support during a visit by a party of the British Association. We were going up the river from the bridge at Ballachulish village (*D*, Map, p. 69). The rocks exposed are the Striped Transition Series connecting the Ballachulish Slates with the Appin Quartzite. They do not afford striking instances of current bedding, and on this account I had deferred any mention of Vogt's reading of the succession, based, as it was, upon quite a different locality. T. C. Nicholas, however, coming up in the rear guard, suddenly claimed that he could read the original order of succession in the light of some current bedding which he had detected. Returning to a little knot of excited disputants, I overheard one of them saying: "This is the opposite of what Bailey thinks, and as we can't decide for certain on the reading, the best thing is to say nothing about it." I thereupon stated Vogt's claim, adding that if it could be firmly established it would render Ballachulish ten times more interesting, for here we should have a district of recumbent folding in which reversed limbs were preferentially thinned.

Accordingly we examined the section very carefully, and I accepted the general opinion that it was indecisive. The following day (in rather unpropitious weather) we looked at Vogt's Tom Meadhoin section (*B*, Map, p. 69). Nicholas again was satisfied, but most of us reluctantly arrived at a verdict of *non proven.*

Next year (1929) Princeton came. Among the many experts who took part in the discussions I may single out T. L. Tanton as especially helpful. Our first attempt was in the river section above Ballachulish bridge (*D*, Map, p. 69). Here, with different people laying stress upon different aspects of current bedding minutiae, the opinion was reached that Nicholas' reading of the evidence was almost certainly correct—or in other words, that this section agrees with Vogt's interpretation of Tom Meadhoin (*B*, Map, p. 69).

Towards the close of the day I took Tanton to a comparatively inaccessible stream exposure of the Appin Quartzite in Allt Guibhsachan (*C*, Map, p. 69). Here the complete quartzite is exhibited, from the Striped Transition Series that links it with the Ballachulish Slates, right on to the Appin Limestone. Starting at the latter and working downstream, Tanton demonstrated again and again to W. B. R. King and myself that the original top of the Appin Quartzite is turned towards the Appin Limestone. *This may be recommended as a completely convincing locality.*

Next day we examined Vogt's section at Tom Meadhoin (*B*, Map, p. 69)—it was raining—and were moderately satisfied with the result. That is, we saw much current bedding; and, though we did not come upon strongly characterized examples, we all agreed that it was easy to find suggestions of the original order of succession, and that these consistently favoured Vogt's interpretation.

That evening Tanton, King and I went to the Onich shore section. We did not know that Vogt had been before us, but we repeated his observations on the eastern crop of the Appin Quartzite (*A*, Map, p. 69). We there found that informative sections are disappointingly few, but in two striking instances the age-orientation of the quartzite clearly supported Vogt's reading of the time succession.

On our return, a Council of Action was summoned. The visitors were already satisfied with the evidence which they had seen demonstrating the recumbent fold of Ballachulish and its attendant slide, and also the refolding of these structures. I, therefore, asked Field whether I might change the programme and enlist the Princeton Summer School for a day's research at the head of Loch Leven (Kinlochleven), where for years I had felt completely baffled by the stratigraphical succession. The facts may be stated very briefly as follows: The type outcrop of the Leven Schists occurs at Ballachulish Ferry, while that of the Eilde Flags crosses the River Leven some distance upstream from Kinlochleven (east of Map, p. 69). In between lie outcrops of quartzite and mica-schist. When I wrote on the district in 1910 I thought that all the quartzite outcrops belonged to one quartzite (Glen Coe Quartzite), repeated by folding, and that all the mica-schist outcrops belonged to the Leven Schists. Later, Carruthers developed the view that three quartzites, separated by two mica-schists, intervene between the Leven Schists and the Eilde Flags. I discussed the two alternatives in the Survey Memoir published in 1916, explaining that I did not know which interpretation to adopt; and until last year (1929) I have felt hopeless of reaching a secure decision without the help of some criterion relating to original order of deposition. Field readily acquiesced, and on the 19th July, 1929, we saw the new method finally disposing of the old uncertainties. We thereupon posted the following letter to Carruthers, carrying twelve signatures:—

"The Princeton Summer School spent yesterday in examining current bedding and erosional channels shown by quartzite outcrops at significant places along the north shore of Loch Leven. It was agreed unanimously that there was sufficient evidence to confirm your three-quartzite and three-mica-schist succession for the district, with the Eilde Quartzite as the oldest member and the Leven Schists the youngest. Without going into detail I may say that outcrops (*b*), (*c*), (*d*), (*e*) and (*f*) of my *Quart. Journ.*, vol. lxvi, map, are all Binnein Schist, leaving only outcrop (*g*) as Eilde Schist. I thought you would like to hear the good news, so I'm sending this signed manifesto as a souvenir."

I have no hesitation in reproducing this letter because I have since returned to the Loch Leven exposures, and have leisurely confirmed with abundant extra detail all the results arrived at on that eventful day. Incidentally, I may add that particularly striking exposures illustrating Vogt's succession occur where the new road south of Loch Leven crosses the type outcrop of the Glen Coe Quartzite (*E*, Map, p. 69).

To sum up certain of the results obtained:—

(1) The stratigraphical succession of the Ballachulish district, with the youngest member placed top of the left-hand column, is as follows:—

Cuil Bay Slates
Appin Phyllites
Appin Limestone
Appin Quartzite
Striped Transition Series
Ballachulish Slates
Ballachulish Limestone
Leven Schists
Glen Coe Quartzite
Binnein Schists
Binnein Quartzite
Eilde Schists
Eilde Quartzite
Eilde Flags

(2) The recumbent fold of Ballachulish is a syncline and indicates movement towards the north-west (the reader must remember that the Ben Lui recumbent fold, at a higher level in the structural sequence, indicates movement towards the south-east).

(3) The Ballachulish Slide is a lag.

(4) The new criterion of original order of succession makes it child's play to recognize the essential structure of the district as recumbent folding, miles in extent, followed by steeply packed folding, thousands of feet in extent. This is particularly clearly seen in the enclosure of the British Aluminium Works, to which the Princeton School gained access through the courtesy of the management. Here the flat bottom of a great compressed syncline is admirably exposed; it is followed on the hillsides to right and left by anticlines of truly grand proportions; and yet examination of the current bedding immediately reveals that all this folding has been executed in materials *previously inverted*. In fact, after taking a series of observations in the Kinlochleven district, Tanton exclaimed: "The original order of succession is everywhere clear, and everywhere it is upside down!"

(5) The great pitch depression which has its north-easterly front near Glen Coe is an integral part of the post-recumbent system of folding mentioned under (4). North-east of Loch Leven this system is developed as a set of steeply packed folds running regularly north-east and south-west. As the pitch-depression is approached these folds tend to exchange their north-east and south-west for a north-west and south-east trend, with many sinuous complications. This matter will be elaborated after further work on the return of summer.

The next thing to do was to write to Vogt and tell him of the signal confirmation of his views, and enquire where his paper had appeared. The letter was forwarded to Trondhjem and was awaiting Vogt on his arrival there to take up his new duties as Professor of Geology. He replied: "Just after my return from Scotland in 1924 I wrote a note upon the subject, and intended to print it in the GEOL. MAG., but did not send it to the redaction, because I did not like to write on the areas of other geologists and colleagues. This summer when I packed my things together in Oslo in order to send them to Trondjhem, I found this MS. note, quite ready to print, again. I am going to send it to you in a few days when my papers have arrived to the institution."

DRAG OR FLOW INSTEAD OF THRUST

There are evidently many issues to be followed up. For the time being let us turn our backs on the complications of Kinlochleven and consider the great folds of Ballachulish and Appin and their attendant slides, the Ballachulish and Fort William Slides (*cf.* Map, p. 69). The reality of these structures has long been established.

It does not depend in any way upon a reading of the original order of deposition. In fact, in my first descriptions (1910, 1916), I was careful to say that the original order was unknown. When, later, in writing of the South-west Highlands as a whole, I had in 1922 to assign an original order to the Ballachulish succession, I pointed out that the only *local* evidence bearing upon the question was the predominance of the Ballachulish and Fort William Slides among the slides of the district. I chose that order of succession which would enable me to interpret these dominant slides as thrusts. Vogt, Nicholas and Princeton have shown me to be wrong. Accordingly the *major slides* of the district are not thrusts but *lags*. I do not think any district elsewhere has ever been described with this tectonic peculiarity. Quite probably the deficiency will be remedied, for Schardt, Termier (with his *traineau écraseur*), and others have strongly insisted upon the importance of drag tectonics in the development of under structures in the Alps—and drag tectonics are assuredly the essence of the Ballachulish story.

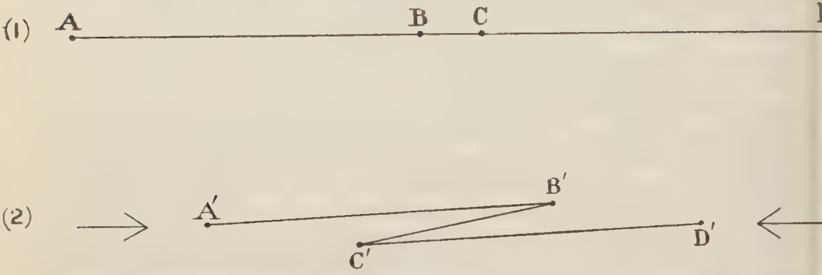

FIG. 2.—Thrust tectonics with overlapping approach of *AB* and *CD*, both maintaining their original lengths. *BC* is rotated and elongated.

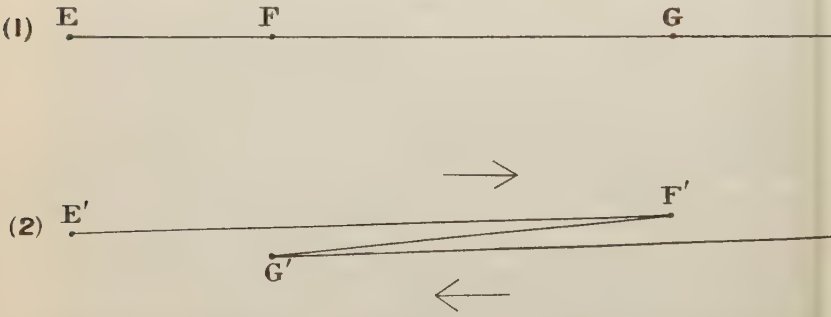

FIG. 3.—Drag tectonics in which *EF* and *GH* are elongated during rotation (without elongation) of *FG*.

Let us illustrate the matter with diagrams. In thrust tectonics, lateral compression compels *AB* and *CD* (Fig. 2) to approach one another with overlap. This involves rotation and elongation of a middle limb *BC*, the initial length of which is often small compared with the extent of final overlap of *AB* over *CD*. Sometimes, even, *B* and *C* coincide to begin with, in which case the reversed limb *BC* is imaginary, or, in other words, is entirely represented by a thrust-plane. Where *BC* starts with a considerable length its subsequent rotation and elongation involve certain features of drag tectonics. So long, however, as the behaviour of the middle limb *BC* is actuated by the approach of the flanking limbs *AB* and *CD*, we may claim that the phenomenon, as a whole, belongs to thrust tectonics. We judge by the final condition of the two flanking limbs. If they retain their original thickness (or have added to it by packing), then we say that they have transmitted the thrust that is responsible for the rotation and elongation of the middle limb. The North-west Highlands furnish classical instances of thrust tectonics.

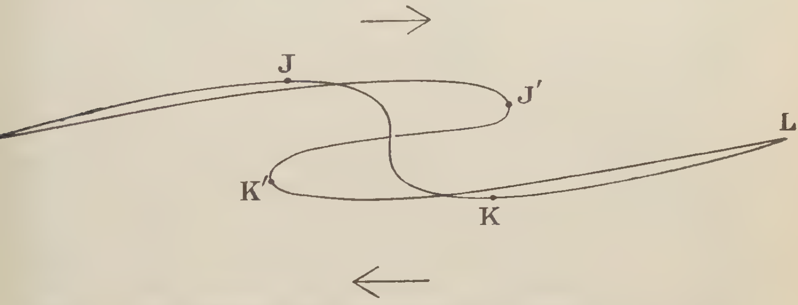

Fig. 4.—Drag tectonics presented less diagrammatically than in Fig. 3.

Drag tectonics are due to distributed shearing stress and may *a priori* be expected in a pliant foundation over which a mountain chain has travelled.[1] The distinguishing feature (I am basing this claim on Ballachulish) is that the rotation of the middle limb *FG* (Fig. 3) elongates the flanking unreversed limbs *EF* and *GH*.

This all seems simple in a sketch a few inches long; but in the Ballachulish district the Leven Schists are lying upside down upon the Ballachulish Limestone for more, probably much more, than 6 miles (10 km.) measured across the strike. We can scarcely suppose that overlying structures rose bodily 3 miles into the air to allow of the rotation of the limb *FG*. There are two mitigating factors. In the first place *FG* would be materially shortened by pressure as it rotated towards the vertical attitude. In the second place it would rotate with curvature, one part after another passing through the vertical. This last condition is illustrated in Fig. 4, where one also sees that more and more of the uninverted limbs

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[1] I do not stress this statement in the present connection because of the evidence of contrary flow furnished by the Ben Lui Fold (p. 81).

IJ and KL tends to be dragged over through the vertical and thus be transferred to the inverted middle limb $J'K'$. There is a vague analogy with what happens when a carpet is unrolled upon a floor.

All that is attempted here is a diagrammatic exposition; and there is only one other factor to which attention will be directed. It is evident that intense compression will be developed in the cores of the recumbent folds that result from the rotation of middle limbs. This compression co-operates with the pull that exists in the uninverted limbs and thus facilitates flow of material towards the rotating crests of the folds.

GRADED BEDDING.

Vogt refers in his paper to a concentration of larger grains in certain positions of the current bedding visible on the Onich shore at A (Map, p. 69). Naturally all the records we possess of current bedding depend upon variations in the nature of the material transported. These variations mark out the current laminae and are readily intelligible. Where, for instance, we see a lamina consisting of particularly large grains we think of it as the product of a particularly strong swish of current. Individual laminae, on close examination, are often seen to vary in constitution along their length and this may produce an aggregate effect upon the constitution of a composite current bed. Thus in many a conglomeratic current-bedded sandstone, the pebbles of individual laminae have *rolled down* to a forward position, with the result that the composite bed acquires a pebbly base. On the other hand in a micaceous current-bedded sandstone, the mica flakes of individual laminae have often been *wafted forward* into a like position, so that the base of a composite bed may be largely composed of mica associated with the smallest quartz grains of the deposit. All such instances are distinct from what I term graded bedding.

In graded bedding a bed of sandstone, ranging from a fraction of an inch to two or three feet in thickness, starts at the bottom with relatively coarse material and grades upwards to relatively fine material (Plates VI and VII, pp. 76, 90). There are wide ranges of texture. Some graded beds are coarse grit at the bottom and pass upwards to fine grit or sandstone at the top (by grit I mean a sandstone in which grain-structure is readily apparent). Others are fine sandstone at the bottom, and pass to sandy mudstone above.

In a succession of graded sandstone beds, if there are no intercalations of other sediments, each plane of stratification is characterized by an abrupt return from relatively fine and muddy to relatively coarse and sandy material. Where, however, graded sandstone beds are separated from one another by independent layers of mudstone, a question sometimes arises as to what is the bottom and what is the top of each individual graded bed. The bottom, of course, remains clearly marked, for its relatively clean sandy and often gritty nature is thrown into additional relief by the definitely muddy composition of the underlying mudstone. On the other hand the upper limit of the graded bed may become comparatively obscure, for here one often encounters nothing more obvious than a junction of sandy mudstone (belonging to the graded bed) and muddy mudstone (belonging to the overlying intercalation). As a rule, however, one feels no real hesitation in deciding upon the plane of separation. There would be no room at all for uncertainty were it not that sometimes an individual sandstone bed, characterized as a unit of sedimentation both by its general sandy composition and its general gradation of texture, is found on close examination to be composite—that is, minor oscillations of texture have developed in its upper portion a faintly marked internal bedding. It is noteworthy that the internal bedding of such a graded composite bed does not (in my limited experience), show current-bedded form, but is either straight or contorted. Contorted bedding or, as it may be styled, slip bedding, is also found among sandstones of the current-bedded class—for instance in the Glen Coe Quartzite along the south shore of Loch Leven (*E*, Map, p. 69). I do not propose to discuss its significance on the present occasion.

It took me many years to realize that *graded bedding and current bedding are the distinguishing marks of two different sandstone facies, the one facies as important as the other*, I first recognized graded bedding—and its significance as a criterion of succession—in a gritty quartzite near the base of the Loch Awe Group, exposed at Kilmory Bay on the shores of Argyll. The occasion was a sunrise visit in the Spring of 1906, during a 60 or 70 mile tramp from Inverary to Tayvallich. I have never lost sight of this observation (1911, p. 64 ; 1913, p. 295 ; 1922, p. 97), but, meanwhile, have missed many comparable examples of graded bedding in other districts. In 1927, however, I was shown the phenomenon in the Coutchiching near Lake Superior, and in the Timiskamian of Porcupine (Plate VII, Fig. 2). I then searched diligently for instances among the quartzites of the Ballachulish district and the sandstones of the Old Red Sandstone, Carboniferous and New Red Sandstone formations of the Central Valley of Scotland. In every case I met repeated current bedding, but scarcely a vestige of graded bedding. Eventually, in the early summer of last year, 1929, D. Tait reported that certain sandstones of the Silurian of the Lesmahagow district commonly show graded bedding ; and a few months later I saw many examples of graded bedding in the Lower Palaeozoic of Wales. The phenomenon is displayed in every degree of definiteness and *dubiety*, so that it is important to give a few type localities where its reality can be recognized without hesitation :—

(*A*) Two localities for coarse-grained examples may be cited, where, in a succession of graded beds, each bed begins with quartz and felspar grains measuring a considerable fraction of an inch in diameter: (1) below the bottom fortification of Harlech Castle, close to Harlech station; (2) in a quarry by the main road at the southern entrance to Barmouth.

(*B*) For fine-grained examples there is no better locality than the Aberystwith shore; here the base of each graded bed is fine sandstone, but is relatively coarse and clean as compared with the top, so that the eye appreciates a much stronger contrast between sandstone and underlying mudstone than between sandstone and overlying mudstone (*cf.* Plate VI, p. 71). I was very kindly directed to Aberystwith by O. T. Jones and I agree with him that its sedimentation phenomena deserve intensive study.

Having seen that graded bedding (and absence of current bedding) are characteristic of many exposures of early Palaeozoic sandstones in Wales, I felt certain that the same must hold good in the Southern Uplands of Scotland. This presumption was based upon the obvious resemblance that exists between the prevalent muddy grits and sandstones of the two districts, and also upon the absence of current bedding in Southern Scotland[1]—a peculiarity that I had long felt required an explanation.

On returning to Scotland I examined with A. M. Bailey the classical folded Silurian of the Berwickshire coastal cliffs between St. Abbs Head and Siccar Point. To our delight we found that graded bedding was incessantly revealed. Two definite localities, where our observations may easily be repeated, are:—

(*a*) In the first haven west of St. Abbs Head, immediately south-west of a low-tide exposure of a neck junction that marks the limit of the St. Abbs Head volcanic rocks.

(*b*) At the entrance to, and within, the ruins of Fast Castle.

Incidentally it may be said that wherever we made observations along this coast-line we found that the orientation of the graded bedding indicates older rocks in the anticlines than in the intervening synclines. It would, therefore, appear that the convolutions of the Berwickshire coast section, made famous by James Hall's descriptions of 1812, affect rocks that were previously not inverted —this important circumstance has hitherto been tacitly accepted without proof.

GREYWACKE.

The Ordovician and Silurian sandstones of the Southern Uplands of Scotland were among the first rocks to be called greywacke outside of the Harz. Robert Jameson, Werner's mouthpiece for Britain, wrote in 1808: " Greywacke is a kind of sandstone, but very different from any of those that occur in the flœtz period. It is composed of grains of sand, which are of various sizes, and sometimes even approach in magnitude to rolled masses. These are connected together by a basis of clay-slate, and hence this rock derives its grey colour and solidity. These fragments are sometimes quartz, sometimes a kind of indurated clay-slate, and sometimes flinty-slate." He added: "It was for a long time supposed that this rock was peculiar to the Harz, where it occurs in great quantity: later investigation, however, have shown that it is widely and abundantly distributed. Besides the Harz, it occurs also in the Electorate of Saxony, on the Rhine, as at Ehrenbreitstein and Oppenheim; Bohemia, Silesia, Moravia, Salzburg, Pyrenees, Transylvania, Tuscany, France, and Portugal; nearly all the mountains in Scotland that lie north [Jameson probably meant *south* because he had just referred to Leadhills and Wanlockhead; in his *Manual of Mineralogy*, 1821, he says, "Greywackes and transition clay-slate abound in all the mountain ranges south of the Frith of Forth, are also frequent to the north of the same boundary, and are widely distributed in England"] of the Frith of Forth, are principally composed of this rock, and many, if not the whole, of the mountains in Cumberland, appear to be of the same nature." (1808, pp. 149–52). When Jameson thus wrote of greywacke he imagined that the type possessed an age significance, which can no longer be maintained. Jameson had quite naturally confounded the unconformity at the base of the Rothliegendes in Germany with that at the base of the Old Red Sandstone in Scotland (the name Old Red Sandstone was transplanted on account of this mis-correlation from Germany to Scotland). The steep greywackes beneath the two red sandstone formations, which in their respective districts mark the beginning of the flœtz, or flat, rocks, were supposed to belong in both localities to Werner's Transition Period. The same kind of mistake was made in regard to the steep sandstones of the Tertiary Flysch of the Canton Glarus in Switzerland. All this has been rectified; but Scottish geologists have continued to employ the name greywacke to denote the particular kind of *muddy* sandstone that is characteristic of the early Palaeozoic developments of Southern Scotland and Wales. Accordingly some of us have viewed with disfavour the modern attempt to re-define greywacke in terms, not of sand and mud, but of basic igneous detritus. This tendency reaches its extreme expression in W. H. Twenhofel's very valuable *Treatise on Sedimentation* (1926), where A. H. Fay's statement is accepted that "Greywacke is a variety of sandstone composed of material derived from the disintegration of basic igneous rocks of granular texture, and thus contains abundant grains of biotite, hornblende, magnetite, etc. It is the ferro-magnesian equivalent of arkose." If this definition be true, then Scottish geologists have been sadly deceived by Jameson. I do not propose to dogmatize on the subject, but offer the following observations.

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[1] Current bedding is well known in the Downtonian of Scotland, but is absent from much of the Lower Palaeozoic sedimentation of the Southern Uplands.

Many of the early Palaeozoic sandstones of Southern Scotland

and Wales are linked by three well marked characteristics. They are typically :—

(1) muddy sandstones ;
(2) without current bedding ;
(3) with graded bedding.

They obviously deserve a distinctive name. The Scottish examples have been consistently called greywacke for more than 120 years. If the original Harz greywackes show the same three characters as are listed above, it would certainly be wise to retain the title greywacke and introduce into its definition a mention of the bedding characteristics of the type. It may be said at once that, while graded sandstones are as a class much muddier than current-bedded sandstones, there is a well marked overlap in this respect. That is, the cleanest of graded sandstones are cleaner than the dirtiest of the current-bedded, or, shall we say, current-washed, varieties.

In conclusion, the question naturally arises : Where in Europe are post-Palaeozoic graded sandstones to be found ? The most tempting place to look for them is in the Flysch of the Alps.

Since this last paragraph was written my attention has been directed to a passage in Marr's recently published *Deposition of the Sedimentary Rocks*. In relation to " embankment " deposits, characterized by interbanding of greywacke and mudstone, Marr writes : " Such Silurian rocks of Britain were long ago regarded by C. Lapworth as having formed under the same conditions as the Flysch of the Alps and adjoining regions " (1929, pp. 105, 128). We shall return to Marr's discussion of " embankment " deposits in the following section.

CONDITIONS OF DEPOSIT.

Current-bedded sandstones are products of currents, and, therefore, belong either to the air or to shallow water. Graded sandstones are products of settling through water under conditions which allow the larger particles to reach the bottom in advance of their smaller comrades. Where, as is often the case, thick formations show repeated examples of graded beds, without intercalation of current beds, it is obvious that the depth of the water has been too great to allow of any but very gentle bottom currents. Let us consider this in relation to the frequent interbedding of graded sandstone and mudstone, and also the characteristic muddy character of graded sandstone. It is clear that the graded sandstones of such a sequence mark the intermittent delivery of a mixture of grit, sand and mud into the waters that overlie the mud floor of the sea *beyond the reach of ordinary sand-pushing bottom currents*. The Nile floods must to some extent be building up graded deposits in the Mediterranean, but it is very improbable that any of the sands so distributed are of gritty texture. Among the graded sandstones of Wales, for instance, at Harlech and Barmouth, there are typical examples in which the grains measure some considerable fraction of an inch in diameter. Did ever a river current propel grains of this magnitude into the surface waters of the sea and leave the bottom tranquil? An alternative is to suppose that each bed of graded sandstone is the record of a hurricane; but the same doubt arises as to the adequacy of hurricanes to distribute coarse material except by developing bottom currents. With these points in view I suggest that graded sandstone beds are often the records of seaquakes (movements communicated to sea water during disturbances of the bottom). The coastal fringe of unconsolidated current-carried sand and mud would provide a source for the material.

After all, there is little novelty in these suggestions. Marr says: "False-bedding is important insomuch as when we meet it we know that we are not confronted with deep-water sediments" (1929, p. 40). He does not, it is true, speak of graded bedding, but he regards the greywacke-mudstone assemblages of North Wales, the Lake District and Gala in Scotland as "deposited by the 'embankment' method on the slopes of the deeps" (1929, p. 104). Where these sediments present fine-textured banding he considers that their rhythm may be seasonal, a view adopted by Coleman and others in similar circumstances (1926, p. 234).

Then, as regards seaquakes, we find the following in Twenhofel's *Treatise*: "About many oceanic islands and the younger continental margins are steep slopes down which materials are readily moved to the deeper waters of the bathyal environment. Such steep slopes lead to inclined deposition and favour slumping, particularly if the steep slopes are the loci of seismic movement" (1926, p. 613). H. A. Brouwer has spoken to me in the same sense, basing upon his knowledge of the East Indies.

Perhaps it is not out of place to say that the present discussion follows naturally upon a paper written in 1928 in conjunction with L. W. Collet and R. M. Field. In it we developed an interpretation of certain submarine landslips, precipitated by tectonic disturbances and seaquakes, in the Early Palaeozoic of Quebec, Canada, and in the Jurassic of Brora, Scotland (1928, p. 577). Our ideas were largely inspired by the writings of H. Schardt on the Flysch of Switzerland and of P. F. Kendall upon the Carboniferous of England. In preparing our paper we overlooked certain apposite references in Twenhofel's *Treatise* (*see* 1926, pp. 524–6).

At this stage it is scarcely worth while elaborating such evidence as may be adduced from internal slip bedding, or the enclosure of angular fragments of previously consolidated mudstone. Those, who would dispose of the whole idea by saying that the individual greywacke beds of the Southern Uplands are too extensive to attribute to seaquakes, should not forget that the same difficulty affects, with greater emphasis, both river and hurricane distribution of the material of these rocks. At all events it cannot be claimed that an excessive number of seaquakes is invoked. The maximum thickness of the Ordovician and Silurian (excluding Downtonian) of Southern Scotland has been estimated as about 15,000 ft. As this includes many rocks besides greywackes, it is reasonable to suppose that there are not more than some 30,000 greywacke beds in any particular part of the district. Modern views give about 60,000,000 years for the accumulation of the composite pile, which roughly corresponds with one greywacke per 2,000 years. and, of course, a seaquake hypothesis retains floods and hurricanes as useful auxiliaries.

ILTAY AND LOCH AWE NAPPES.

The discussion of graded bedding has carried us far from the Scottish Highlands; but let us in conclusion return to this district. In 1922, I grouped the South-west Highlands into three structural divisions as follows :—

Loch Awe Nappe;
Iltay Nappe;
Ballappel Foundation.

In each of them I suggested an original order of succession. In the Ballappel Foundation my order, which was not based upon direct local evidence, has been proved wrong. In the other two, where direct local evidence had already been obtained (*cf.* 1922, pp. 97, 101), renewed search, in company with A. M. Bailey, has last Autumn, 1929, brought strong confirmation.

Iltay Nappe.—The junction of the Ben Eagach Black Schist and Carn Mairg Quartzite runs, almost vertical, up the slopes of Cammoch Hill, west of Pitlochry in Perthshire. Zig-zagging in our ascent, we crossed and recrossed repeatedly that portion of the quartzite which lies near the Black Schist. We saw no current bedding, but about 50 examples of graded bedding, all pointing to the conclusion that the Black Schist is later than the Quartzite. It is probable that a comparatively few beds furnished all the evidence that we obtained; but in some exposures three or four beds could be seen in succession, all graded in the same sense. The phenomenon is not strongly marked in this exposure, owing, perhaps, to the fairly pure nature of the original sand.

Loch Awe Nappe.—Three localities were visited in the neighbourhood of Loch Awe south of Dalmally. These localities can be identified on the Geological Survey Map, Sheet 45.

(1) H. Kynaston in the Geological Survey Memoir on Sheet 45 (1908, p. 28), says: "The base of the quartzite is well seen on the south side of Allt Fearna, to the east of Inistrynich, where it rests upon grey silvery phyllites with limestone bands. The actual base is here often coarse and pebbly, and contains numerous fragments of limestone identical with that exposed immediately below it, and the junction, in the opinion of Mr. Kynaston, has all the appearance of an unconformity." We found good exposures south

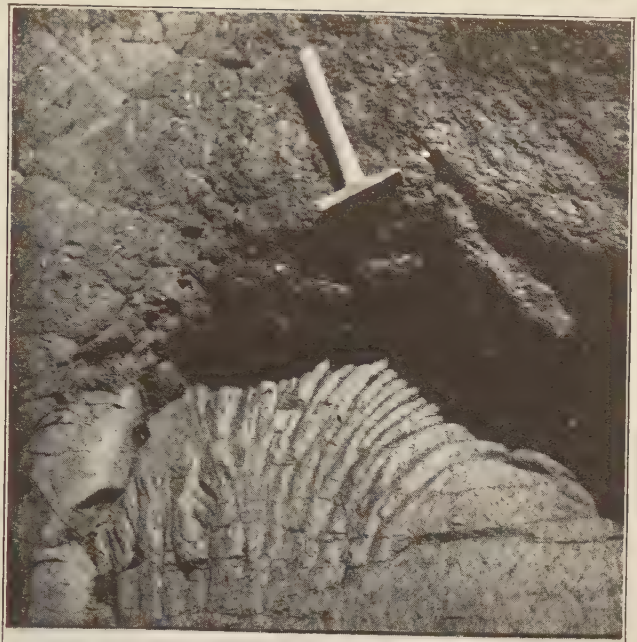

FIG. 1.—FLOW WRINKLES ON BASALTIC LAVA, L. SUPERIOR. (*See* T. L. Tanton.)

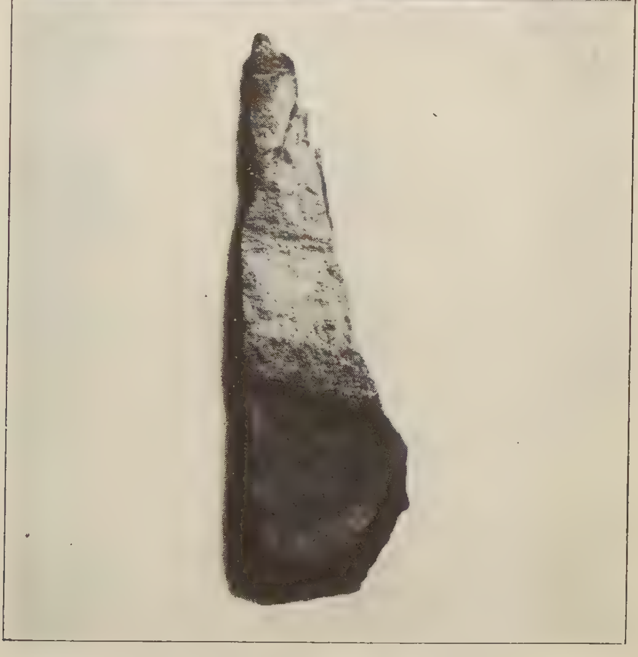

FIG. 2.—GRADED BEDDING, TIMISKAMIAN, PORCUPINE. × $\frac{1}{2}$ Sandstone grades down into grit, which lies abruptly on mudstone. (*See* E. B. Bailey.)

of the stream (Allt Fearna) towards the east end of a clump of trees. The base of the quartzite is traceable for a hundred yards or so, at places forming an overhanging roof to exposed limestone. The basal part of the quartzite is a particularly coarse grit, in which the quartz grains, often bluish, reach up to three-quarters of an inch in length. For 10 ft. up in the quartzite there are frequent angular ochreous fragments representing limestone ; most of them are less than an inch long, but one was noticed measuring eight inches. The quartzite above the basal 10 ft. is generally finer in texture, though there are still some fairly coarse layers. In this upper part limestone fragments do not occur. There are indications of shearing at the base of the quartzite, but I do not think that anyone would doubt that the contact is essentially sedimentary (not tectonic). In fact it seems obvious that the quartzite has derived material through erosion of the underlying limestone. That is, the Crinan Quartzite of the Loch Awe Group is later than the Shira Limestone of the Ardrishaig Phyllites.

(2) The next interesting exposure lies about a quarter of a mile to the south across a shallow syncline. It measures some 30 yards in length. Here gritty quartzite rests at a low angle on limestone. There are three layers containing limestone fragments. The lowest of them is about 5 ft. thick towards the south-west where it occupies a basal position, but is completely over-lapped towards the north-east. Careful examination shows clear indications of erosional surfaces within the quartzite. There are also two examples of quartzite beds grading up from coarse to fine. This exposure is absolutely conclusive in its confirmation of (1).

(3) A mile and a half farther south-east, the Geological Survey Map shows a driftless exposure of quartzite and limestone in Allt an Stacain. The section lies along the steeply inverted edge of a syncline, where quartzite plunges under limestone. The stream (Allt an Stacain) has at one point bared an unsheared contact of the two formations. A few yards farther up-stream, on the south-east bank there is a somewhat extensive cross-strike exposure of quartzite, beginning practically at the limestone margin of the formation. The conditions favour close scrutiny, and it is easy to recognize grading in several of the quartzite beds. In all cases these graded beds turn their original bases towards the limestone side of the exposure. That is, once again, the Crinan Quartzite is seen to be later than the Shira Limestone.

SUMMARY.

1. The Loch Awe Nappe succession was correctly stated in 1922.
2. The Iltay Nappe succession was correctly stated in 1922.
3. The Ballappel Foundation succession was wrongly stated in 1922.
4. The recumbent-fold structure of the Ballachulish district is due to rotation of middle limbs by drag from above or from below.

5. Graded bedding is as important as current bedding in marking a facies group among sandstones. It often indicates accumulation in rather deep water, to which sandy material has penetrated, perhaps as a result of seaquakes.

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REVIEWS.

ORE DEPOSITS OF MAGMATIC ORIGIN: THEIR GENESIS AND NATURAL CLASSIFICATION. By PAUL NIGGLI. Translated by H. C. BOYDELL. pp. xi + 93. London: Thomas Murby & Co., 1929. Price 9*s*. 6*d*.

THE original German edition of this book was reviewed at some length in this MAGAZINE (Vol. LXIV, 1927, p. 88). It is a matter of much satisfaction that so important a work has now been made accessible to English readers, and that the translation has been placed in the capable hands of Dr. Boydell. It has also had the advantage of revision by the author and Dr. R. L. Parker, who have introduced certain additions and improvements of the text. It is perhaps permissible to hope that petrologists in general may now be brought to realize the interest of the latest stages of magmatic activity, which most of them up to the present time have studiously ignored, at any rate in this country.

GEOLOGY OF GOLD. By E. J. DUNN. pp. x + 303, with frontispiece, 251 figures, and 172 diagrams. London: Charles Griffin and Co., Ltd., 1929. Price 35*s.*

THE author of this fine book has had practical experience of his subject extending over more than half a century in South Africa, Australia, and New Zealand. As most geologists are well aware, he was one of the pioneers of geology in South Africa. The earliest of his publications quoted in Hatch and Corstorphine's bibliography is dated 1873, and in 1875 he published a geological map of South Africa, a sufficiently remarkable achievement at that date: while the reviewer believes that he was the inventor of that now world-famous name, the Dwyka Conglomerate. After removing to Australia he continued geological work with unabated vigour for many years, particularly with reference to the geology of gold. In the course of this long career Mr. Dunn naturally made an immense number of valuable observations, many of them of things no longer accessible. The present book therefore is of very great value even if only considered as a record of things seen, and many of the diagrams are of great interest and admirably clear: they have the advantage of being printed on plate paper.

Besides records of fact and observation the book also contains much discussion of points of geological theory, and in this field some of the author's views are at least a little unorthodox. For example, referring to granite, he writes, "That it is an igneous rock of similar origin to the purely intrusive and effusive rocks whose origin is known, cannot be accepted." Few, if any, geologists will agree with this statement. The author appears to be in fact an advocate of an extreme form of assimilation, an idea which is negatived by the absence of a sufficient degree of superheat in a magma, as argued by Bowen. Stress is rightly laid on the greater frequency of gold deposits, and one might add of mineralization generally, in connection with granodioritic types rather than with the more highly alkaline granites. The economic metals, except perhaps tin and tungsten, seem to fight shy of extreme alkaline differentiates, while the rare earths are at home in them. The nearly pure quartz veins in which so much gold is found can evidently be formed from any kind of acid or even intermediate magma, however poor in alkalies. Although Mr. Dunn states that gold-bearing quartz is not of igneous origin, nevertheless his explanations imply that it is at any rate hydrothermal, as it undoubtedly is, and therefore in reality late-magmatic. There is a very interesting discussion of the effect of certain rocks, e.g. particular bands of slate or diorite dykes, in causing selective precipitation of gold, as exemplified specially at Bendigo and Ballarat, where slate indicators have been of great value in development.

It is, however, impossible to enumerate all the points of interest raised in this book, which should be read by all who are interested in the geology of gold.

OBITUARY.

William Hewitt, Hon. M.Sc. (Liverpool), B.Sc. (London), Assoc. R.S.M.

BORN, 30TH AUGUST, 1851. DIED, 27TH NOVEMBER, 1929.

The death took place on 27th November, 1929, in his 79th year, of Mr. William Hewitt, who was widely known in educational and scientific circles. He was born at Keighley, Yorkshire, on 30th August, 1851, and was educated at the Royal School of Mines, where he had among his teachers, T. H. Huxley and (Sir) A. C. Ramsay. He took his B.Sc. degree at London University in 1876, with first class honours in Zoology, and also in Geology and Palaeontology. In 1877 he went to Liverpool as Science Demonstrator for the School Board, a position he held until 1892, when he was appointed to the newly created post of Director of Technical Education, retiring on superannuation under the age limit in 1916. In that capacity his chief life-work was accomplished, and to his untiring zeal and organizing abilities the high standard of efficiency of technical instruction in the City at the present day is largely due.

In spite of the onerous nature of his official duties, he found time to interest himself in the Learned Societies of the district, and since his retirement had devoted himself more than ever to their work and welfare. He was especially interested in geology, and at his death had completed 52 years' membership of the Liverpool Geological Society. He served it as hon. secretary for five years, as hon. treasurer for four years, and was President for the sessions 1891–2, 1892–3, 1910–11, and 1911–12. Two of his presidential addresses to the Society, viz. "The Physical Conditions of the Aralo-Caspian Region as bearing on the Conditions under which the local Triassic Rocks were formed" (1892) and "The Physical Conditions under which the local Triassic Rocks were formed" (1910), are valuable contributions which have been frequently referred to by succeeding workers. Among many other papers one entitled "Notes on Pebbles in their Geological Associations" (1918) may be mentioned, in which much useful information, partly based on original investigation, is recorded. On the celebration of the Society's jubilee in December, 1909, he published "A Retrospect of Fifty Years' Existence and Work", which, in addition to much interesting historical matter, contains a valuable discussion of local geological problems and investigations. His work was recognized by the award to him of the Society's medal in 1921.

On the occasion of the meeting of the British Association in Liverpool in September, 1923, he acted as local secretary of Section C (Geology), and also contributed to the handbook "Merseyside", in addition to other chapters, that on "The Geology of the Country around Liverpool". He took a constant interest in the Geological Department of Liverpool University from the time of its establishment in 1916, and for a brief period during the War lectured there in the absence of the Professor. In July, 1929, the honorary degree of M.Sc. was conferred upon him by the University. Towards the equipment of the new departmental building of Geology opened in October last, he made a generous contribution.

For some years he acted as honorary director of the Liverpool and District Regional Survey Association, and his interest in its work led him to compile his well-known book on " The Wirral Peninsula—an Outline Regional Survey ", as well as to write many papers of value to the student of the history and progress of Wirral. All his work was characterized by painstaking care and high conscientiousness, and he was esteemed by all who knew him.

T. A. JONES.

CORRESPONDENCE.

IRON-RICH CORDIERITE.

SIR,—Now that the composition of cordierite is once more the subject of discussion (H. H. Read, GEOL. MAG., Vol. LXVI, 1929, p. 547) it may not be out of place to refer to a recent study by Ramdohr of the iron-rich contact rocks around the Brocken massif (*Neues Jahrbuch für Min., etc.*, 1927, A. p. 333). Ramdohr describes cordierite rocks resulting from the thermal metamorphism of iron-ore rocks, particularly mineralized tuffs, the cordierite being associated with an iron-olivine and a hercynite spinel. The bulk analysis of the rocks (e.g., one from Spitzenberg-Klippen, *op. cit.*, p. 377) is sufficient to show that these cordierites may be added to the list of iron-rich cordierites compiled by Dr. Read. The interest of the contact-altered iron-ore rocks of the Harz, however, lies rather in the nature of the assemblages developed. A fayalite-hercynite-cordierite hornfels is an assemblage described for the first time. This assemblage is one of especial interest. In a note on the paragenesis of the minerals of the system MgO-Al_2O_3-SiO_2 (GEOL. MAG., Vol. LX, 1923, p. 101), I observed that whilst in artificial melts the association cordierite-forsterite occurred, amongst natural rocks the pair was represented by a spinel-enstatite assemblage. A reversible transformation spinel + enstatite $\rightleftarrows$ cordierite + forsterite was suggested, the left hand pair representing the low-temperature association under the conditions of metamorphism. In the corresponding system FeO-Al_2O_3-SiO_2, however, it seems clear that the cordierite-fayalite assemblage is the stable association under similar conditions. The field of existence of iron-orthopyroxene is unknown and is clearly not realized among the contact rocks of the Harz, for fayalite-quartz assemblages are recorded by Ramdohr. At lower temperatures in the presence of water these latter minerals react to give an amphibole (iron-anthophyllite or gruenerite) while the fayalite-cordierite pair pass to an aluminous gedrite. Rankin and Merwin, in their study of the system, MgO-Al_2O_3-SiO_2, expressed the view that the introduction of iron into the system might lead to the disappearance of the cordierite field, a suggestion which is now the less convincing. The many pressing petrological problems associated with equilibria in iron-containing silicate systems—of which this is one—would doubtless soon find their solution if some advance could be made in overcoming the great experimental difficulties associated with the investigation of these systems.

C. E. Tilley.

A NOTE ON THE HOLYWELL SHALES.

Sir,—The report in your issue of January last of the paper by Messrs. W. Lloyd and R. C. B. Jones on " The Upper Carboniferous of Flintshire ", read before the Manchester Geological Association on 12th November last, shows that valuable results have been obtained, and the publication of the full paper will be awaited with interest.

The identification by Dr. J. W. Jackson of *Posidonomya corrugata*, the fossil previously referred in error by me and others to *P. becheri*, from beds resting on the chert near Holywell, shows that in that district the *P* beds have been cut out.

I showed in a former paper (this Magazine, Vol. 64, 1927, p. 252) that on the northern fringe of the chert outcrop the lowest shales resting on the chert are of *P* age, with undoubted *P. becheri*. At Holywell, seven miles to the south-east, it now seems clear that the lowest shales are of low *E* age. Still further to the south-east, in the neighbourhood of Hope, the lowest shales (*fide* Lloyd and Jones) are of upper *E* age, with *Eumorphoceras bisulcatum*.

It seems clear, therefore, that there is a definite overlapping of the shales from north-west to south-east and the occurrence of *P. corrugata* at Holywell does not in that case indicate (as suggested in the report) any change in the stratigraphical position of the Chert-beds. These beds are seen resting directly on the Carboniferous limestone at many points from near Prestatyn on the north of the Chert outcrop to Moel-y-Gaer on the south, including the intermediate Holywell district.

The transgression is still further emphasized at Nant-y-Figillt, south of Moel-y-Gaer, where the authors report *G. cancellatum* and *R. reticulatum*, mut. γ, a short distance above the limestone.

I venture to think that there can be no doubt that the Chert-beds are of Lower Carboniferous age, and, judging from the abstract of their paper, the authors' valuable work shows that the Holywell Shales rest upon them unconformably and overstep them on the south.

H. C. Sargent.